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Incremental dynamic analysis of nonlinear rocking soil-structure systems

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ABSTRACT

Rocking isolation effect on seismic demands of shear-building structures rested on shallow foundation is investigated in this paper. Building structures with surface raft foundations of various geometrical and structural properties located on soft-to-very dense sites are studied. Two types of near-fault pulses, i.e. fling step and forward directivity, are considered as input excitation. Results show that nonlinear SSI effect is governed by static vertical safety factor of foundation (F_S) that is varied in this study. Evidently, it is not necessary to excessively decrease the F_S factor. So that rocking isolation is achieved as F_S factor is around 2.0. On the other hand, nonlinear SSI effect is strongly correlated with normalized period of the incident near-fault pulse (T_p/T). The most significant effects of nonlinear SSI on mitigating structural demands occur at T_p/T near to unity. It is observed that rocking isolation has the same drawbacks of conventional synthetic translational isolators that work in sway directions. The first drawback is deficiency of rocking isolation subjected to long-period near-fault pulses and the latter is in case of high-rise superstructures.

1. Introduction

Near-fault earthquake records have some distinct characteristics compared to far-fault records. High-frequency components in acceleration time history namely background records as well as long-period velocity pulses are among notable specifications of such ground motions. For the first time, Alavi and Krawinkler [1] postulated that equivalence between a near-fault ground motion and a corresponding pulse can be reasonably established. If the ratio of fundamental structural period (T) to pulse period (T_p) stands in a certain range, the primary near-fault record can be well represented by simple pulse models. In such condition, no significant bias is expected in seismic response evaluation of the structural system.

Accordingly, the possibility of replacing a simple pulse model with actual near-fault ground motions has motivated researchers to introduce various simplified pulse models during recent years (examples: [2–6]). Using these simplified synthetic pulse models, Kalkan and Kunnath [5] investigated the consequences of renowned features of near-fault ground motions on the seismic structural responses. Simple sine pulses, previously proposed by Sasani and Bertero [3], were also adopted to simulate directivity and fling effects. The investigations have shown that adequate consistency exists between the results of synthetic pulses and real near-fault ground motions. Xu and Agrawal [7] observed that the influences of mathematical pulse models are similar to the extracted pulse components. Moreover, they concluded that pulse-type portions of real near-fault records are the main cause of the maximum elastic and inelastic demands of structures.

On the other hand, it is well known that dynamic soil-structure interaction (SSI) can influence seismic performance of structures during strong near-fault shakings. Basically, SSI can have two types of effects on seismic performance of structures. The former, namely linear effects, accounts for (i) elongation of natural period of soil-structure system and (ii) mostly increase in damping parameters compared to the fixed-base condition [8,9]. The latter, namely nonlinear SSI effects, is mainly due to foundation uplifting, soil yielding, and foundation sliding.

First, foundation uplifting is a geometrical nonlinearity that means zero tensile strength between the shallow foundation and the underlying soil. Second, soil yielding is a material nonlinearity that includes inelastic behaviour of the underlying soil [10]. Third, foundation rocking is an important component of the foundation motion, especially in case of slender structures.

Radiation and material damping of the underlying soil can significantly dissipate the seismic energy and drastically influence the structural responses [11]. Some researchers have investigated the SSI effect. For instance, Luco et al. [12] performed forced vibration field tests for a 9-story reinforced concrete building to study the SSI effect. The tests indicated that the SSI had significant effects on the dynamic properties of the building and the rigid-body motion caused by the translation and rocking of the base accounted for over 30% of the total response on the roof.

Gazetas et al. [13] showed that an engineering apparent seismic factor of safety less than 1.0 does not imply failure in seismic

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geotechnical design. It was also demonstrated that in many cases it may be beneficial to underdesign the foundation by accepting substantial uplifting and/or full mobilization of bearing capacity failure mechanisms. This context so-called “rocking isolation” is a relatively new design paradigm advocating the intense rocking response of the superstructure as a whole, instead of flexural column deformation. This is accomplished through deliberately underdesigning the foundation in order to guide plastic hinging below the ground surface, rather than in the columns.

As another investigation, Anastasopoulos et al. [14] used a two-story two-bay asymmetric frame to explore the effectiveness of this novel design approach. Finite element dynamic analyses were performed using idealized pulses and a set of 20 real accelerograms, taking into account material (soil and superstructure) and geometric (uplifting and P-Δ) nonlinearities. A conventionally Eurocode-designed frame and its foundation were compared with a design featuring the same frame, but with substantially under-designed (“unconventional”) footings. They observed that the performance of the unconventional system is advantageous, as not only does it escape collapse, but as it also enjoys repairable damage. Despite the footings’ reduced width, the residual settlements of the under-designed footings were comparable to those of the conventional ones. However, the analyses also revealed that residual rotation and differential settlement of the underdesigned footings may be unavoidable and must be critically evaluated.

Based on more recent findings, some numerical models are documented in the literature for more realistic prediction of nonlinear soil-foundation interaction from the research domain to a form useful for practical application. One of these models, namely beam-on-nonlinear-Winkler foundation (BNWF), was proposed by Raychowdhury and Hutchinson [15] which is used in present study.

The aim of this paper is estimating the effects of nonlinear SSI on shear-type building structures. For this purpose, mid-to-high rise shear building structures with surface raft foundations having a wide range of geometrical and structural properties located on soft-to-very dense sites are studied. Two types of near-fault ground shocks are considered as input excitation. Idealized mathematical functions are used to represent low-frequency near-fault directivity and fling pulses. The superstructure is assumed to be a regular shear building including P-Delta effects. The underlying soil is simply modeled with an ensemble of nonlinear springs and dashpots following the Beam-on-Nonlinear Winkler Foundation (BNWF) concept. Using Incremental Dynamic Analyses (IDA), seismic response of soil-structure system subjected to near-fault pulses is evaluated in three alternative conditions including: fixed-base, linear, and nonlinear SSI. Then rocking isolation effects due to foundation uplifting and soil yielding are discussed.

2. Numerical model

The soil-structure system modeled in this study consists of a multi-story building structure based on a surface mat foundation located on soil medium. Conceptual scheme of the numerical model is schematically illustrated in Fig. 1. As shown, the soil-foundation-structure system is subjected to two types of near-fault pulses. Further descriptions on superstructure and interacting system are presented in the following.

2.1. Superstructure

Shear building models are most commonly used in research studies on seismically isolated buildings. To this aim, a generic simplified model is created to represent a class of structural systems with a given natural period and distribution of stiffness over the height [16]. In this study, the superstructure is a shear building regular in plan and height in order to avoid the effects of geometrical asymmetry. Requirements for including near-fault effects are considered according to ASCE7-10 [17]. Dead and live loads are assumed 600 and 200 kg/m^2,

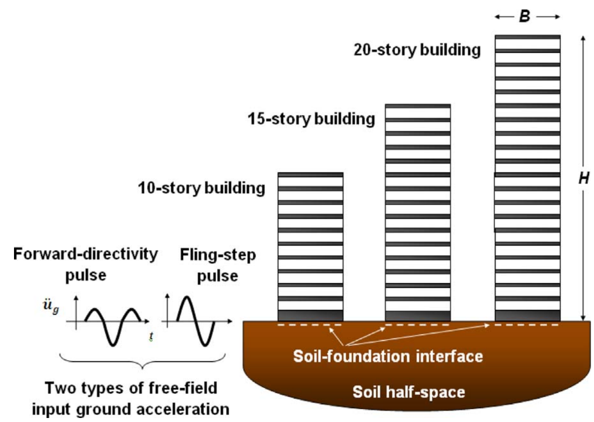

Fig. 1. Soil-structure systems subjected to near-fault ground shocks.

respectively. The story height of 3.0 m and number of stories equal to 10, 15, and 20 are selected in order to represent medium-to-high rise buildings that can rationally be supported by shallow foundations on different types of soil medium. More detailed information on geometrical properties of the superstructure is presented in Table 1.

First-mode natural periods of fixed-base structure are 1.0 s, 1.5 s, and 2.0 s for 10-, 15-, and 20-story buildings, in the same order. These natural periods are consistent with approximate fundamental period formulas introduced in ASCE7-10. The analyses have been performed using OpenSEES software [18]. Also, Rayleigh damping model is used, in which the damping ratio of superstructure is assumed to be 5% of critical damping.

Two alternative assumptions are attributed to the superstructure model in this study:

- ***Model Type A***: In this case, the superstructure is simulated as a multi-story shear building with elastic behaviour in order to incorporate higher-mode effects but excluding structural inelasticity. For this purpose, all superstructure elements are assumed to stay within elastic limit using elastic beam-column elements. On the other hand, P-Delta geometrical nonlinearity is included.
  More details on modal properties of the superstructure are presented in Table 2. The lateral stiffness values given is Table 2 consist of pure shear as well as flexural stiffness. The flexural stiffness is mainly due to axial deformability of the column members that is considered in this study, as elastic beam-column elements are used for column members.
- ***Model Type B***: To examine the effects of structural inelasticity, equivalent single-story shear building with inelastic behaviour is also defined in accordance with recommendations of FEMA440. The geometry, mass, and stiffness properties of the single-story model are defined to represent first-mode characteristics of the original multi-story fixed-base structure. In this case neglecting higher-mode effects, structural inelastic demands are considered. Bilinear elastic-perfectly plastic material with 5% strain hardening ratio is assigned to the interconnecting elements between lumped mass of the equivalent single-story superstructure and the foundation along

Table 1
Building geometry.

No. story	Slenderness Ratio, *SR*	Plan dimension (m)	No. spans	Length of span (m)
10	2	15.0	3	5.0
	4	7.5	2	3.75
15	2	22.5	4	5.63
	4	11.25	3	3.75
20	2	30.0	5	6.0
	4	15.0	3	5.0