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Rocking isolation of nonductile moderately tall buildings subjected to bidirectional near-fault ground motions

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ABSTRACT

Recent studies show that slender structures with shallow foundations located on soil medium can benefit from rocking isolation effects during strong earthquakes. In such condition, foundation uplifting and soil yielding provide supplemental energy dissipation potential at substructure level. As a result, the structural demands would be significantly reduced. In this study, building structures with various geometrical properties mounted on surface raft foundations are examined. A set of 91 component pairs of near-fault forward-directivity ground motions recorded at soft as well as dense sites are selected. Three dimensional nonlinear soil–structure interaction (SSI) including foundation uplifting and soil yielding is considered. The results show that the protective effects of rocking isolation can play vital role in survival of medium-to-high-rise building structures subject to catastrophic earthquakes which are excessively greater than design limits. Evidently, rocking isolation has enhanced the elastic structural demands up to 50% for low-aspect-ratio as well as 75% for high-aspect-ratio structures. Such beneficial effects keep the superstructure in significantly larger safety margins. In addition, site effects on seismic demands of rocking structures, as well as liquefaction potential in case of buildings located on soft site are investigated.

1. Introduction

Soil–structure interaction (SSI) can affect seismic performance of structures in two ways: (i) the linear effects of SSI including elongation of natural period of soil–structure system and mostly increase in damping parameters compared to fixed-base structure [1–3] and (ii) the so-called nonlinear effects of SSI due to foundation uplifting, soil yielding, and foundation sliding [4–8]. Soil elastoplastic behavior during foundation motions is called soil yielding as a material nonlinearity [9]. Uplifting is a geometrical interface nonlinearity due to detachment of foundation–soil interface. It is triggered when eccentricity of vertical load subjected to the foundation exceeds some thresholds. Also, slippage of contact area of foundation on subgrade soil when base shear exceeds the frictional strength of the interface leads to another interface nonlinearity so-called foundation sliding [10]. But it is worth mentioning that lateral deflection of the tall building under earthquakes will be very much larger than the lateral translation of its foundation. Thus, horizontal movements of the foundation system can usually be ignored. However, a small rotation at the base of a building in rocking structures can result in significant lateral displacements at top levels of high-rise buildings. Accordingly, foundation sliding phenomenon in seismic response of rocking-dominated moderately tall buildings is ignored in this study [11].

Near-source seismic records have some important characteristics that make them different from far-field ground motions. High-frequency component in acceleration records, namely background record, as well as long-period velocity pulses are among notable specifications of such ground motions. If the extracted pulse is “large” relative to the remaining features in the record, the ground motion is classified as pulse-like [12]. These pulse-like ground motions have been identified as imposing extreme demands on structures to an extent not predicted by typical measures such as response spectra [13–15]. Long-period velocity pulses in near-fault ground motions may have different seismological bases (e.g. forward rupture directivity, tectonic fling step, etc.). Among different types of long-period velocity pulses, it has been demonstrated that the near-fault pulses with large amplitude and potential directivity characteristics, have the most destructive effects on seismic performance of the structures [12]. In order to quantify the special effects of forward directivity and to develop appropriate design guidelines, much effort has been devoted to analysis and seismic performance evaluation of elastic and inelastic systems subjected to such excitations [13,14,16–18].

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In this paper, nonlinear effects of three dimensional SSI including foundation uplifting and soil yielding subjected to bidirectional near-fault ground motions are investigated. Considering strong shakings of near-fault events, it is expected that rocking isolation effect of nonlinear SSI plays important role in seismic performance of soil–structure systems [7,8]. This fact is elaborately examined in case of bidirectional near-fault excitations in present study. To this end, an extensive parametric study is conducted. Medium-to-high-rise building structures with different slenderness ratios based on surface raft foundation with different plan sizes (i.e. different vertical load-bearing safety factors) located on soft-to-very dense soil are investigated. Elastic response of the superstructure including P-Delta effects is evaluated in this study. Two comparative SSI conditions (i.e. with versus without uplifting and soil yielding) are assigned to soil–foundation interface. A set of 91 component pairs of forward-directivity pulse-like ground motions recorded at soft and dense sites is selected as input excitation. The assessments provide further insight into soil–foundation–structure interaction problem concerning rocking isolation context. The outcome of this study is quite promising to be useful in practical design purposes.

2. Soil–structure model

The soil–structure model consists of a multi-story building based on a surface mat foundation located on soil medium. The superstructure is a three dimensional shear building regular in plan and height to avoid the effects of geometrical asymmetry. Service loads of the buildings are considered according to ASCE7-10 [19]. Dead and live loads are assumed 600 and 200 kg/m^2, respectively. The story height is assumed to be 3.0 m and number of stories is equal to 10, 15, and 20. Such range of structural height can represent medium-to-high-rise buildings that can rationally have shallow foundations on different types of soil medium. First-mode natural periods of fixed-base structure are 1.0, 1.5, and 2.0 s for 10-, 15-, and 20-story buildings, respectively. These natural periods are consistent with approximate fundamental period formulas introduced in ASCE7-10. All superstructure elements are assumed to stay in elastic limit using elastic beam–column elements and P-Delta geometrical nonlinearity is included. By assuming elastic superstructure, the source of nonlinearity would be mainly localized in the substructure. Finite element (FE) models of the soil–structures systems are analyzed using OpenSEES software [20] according to nonlinear dynamic analysis procedure. Also, Rayleigh damping model is used, in which the damping ratio of superstructure is assumed to be 5% of critical damping. Typical 10-, 15-, and 20-story shear buildings subjected to bidirectional near-fault ground motions are illustrated in Fig. 1.

The foundation is a square mat with thickness of 1.0, 1.5, and 2.0 m for 10-, 15-, and 20-story buildings, respectively. Brick elements are used to model the foundation. Dimensions of the foundation plan are designed according to vertical load bearing capacity of soil medium. The foundation is assumed to be rigid and no embedment is considered.

Four types of soil media with a wide range of shear-wave velocity (V_s) are considered to cover soft to very dense soil in accordance with site classification introduced in ASCE7-10. Soil density which is correlated with shear-wave velocity has been set equal to 2.3 t/m^3 for shear-wave velocity greater than 750 m/s and 1.9 t/m^3 for shear-wave velocity smaller than 750 m/s.

The soil Poisson's ratio has been assumed 0.33. Simplified models are used to represent substructure's behavior including soil flexibility, radiation damping, tension cut off, and soil yielding.

Nonlinear hysteretic damping is adopted using frictional elements to consider material damping of the soil. Meek and Wolf demonstrated that nonlinear hysteretic damping independent of frequency is more suitable and can be introduced by frictional elements, which permit causal analysis in the time domain [21]. In this research, frictional elements are employed for analyzing the soil–structure system and material damping of the soil is assumed 5%.

The horizontal (sway) impedances can be directly obtained using Cone model formula [3]. However, rocking and vertical impedances, because of nonlinear effects of foundation uplifting and soil yielding, could not be directly calculated using lumped model in vertical and rocking directions. To solve this problem, instead of using a unique lumped mass foundation model in vertical and rocking directions, the foundation area is discretized over a sufficient number of nodes. The discretization of foundation plan area has been done in accordance with so-called subdisk method recommended by Wolf to calculate vertical and rocking dynamic impedance of soil [22]. In subdisk method, a foundation of any desired shape may be modeled by an assemblage of such subdisks that can be replaced with primary global foundation area in vertical and rocking directions. Further details on subdisk method assumptions are discussed by Wolf [22]. To include foundation uplifting and soil yielding in finite element modeling of soil–structure system, the vertical nonlinear gap elements are assigned to centers of subdisks as sketched in Fig. 2 on the right.

3. Earthquake data

A database including 91 pairs of fault-normal and fault-parallel components of near-fault earthquakes from Next Generation Attenuation (NGA) ground motion library is used. They are the same records as used by Baker within each pair of which the fault-normal component has magnitude greater than 5.5, absolute velocity amplitude larger than 30 cm/s, which are recorded within 30 km of an event [12]. These records meet all criteria to classify as pulse-like near-fault ground motions. These criteria identify ground motions of engineering interest because of their large amplitude and potential directivity effects. Component pairs of near-fault records ensemble are listed in Table 1.

It is found that inelastic rocking effect increases under biaxial excitation, while it is less sensitive to the vertical component of the earthquake [23]. Accordingly, the record sets do not include the vertical component of ground motion. Ground motion component pairs are not scaled to any specific intensity in order to enable more realistic judgment on nonlinear SSI effects induced by near-fault bidirectional earthquakes of different magnitudes. To make more reliable assessments, the number of records ensemble is increased sufficiently. The 91 selected component pairs are recorded at soft as well as dense sites as introduced in Table 1 in accordance with site classification of ASCE7-10.

4. Nondimensional parametric framework

It is well known that the response of soil–structure system depends on geometric and dynamic properties of the structure and the underlying soil. These effects can be incorporated into the model by the following nondimensional parameters [24,25]:

$$a_0 = \frac{\omega_{fix} H_n}{V_s} \quad (1)$$

$$SR = \frac{H_n}{B_{str}} \quad (2)$$

where a_0, ω_{fix}, H_n, V_s, SR, and B_{str} stand for nondimensional frequency, circular frequency of the fixed-base structure, superstructure height, shear-wave velocity of soil, slenderness ratio, and width of the superstructure, in the same order. Nondimensional