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Dynamic responses of structure–soil–structure systems with an extension of the equivalent linear soil modeling

M. Ghandil, F. Behnamfar*, M. Vafaeian

Department of Civil Engineering, Isfahan University of Technology, Esfahan 8415683111, Iran

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ABSTRACT

A three-dimensional problem of cross interaction of adjacent structures through the underlying soil under seismic ground motion is investigated. The story shears and lateral relative displacements (drifts) are the targets of the computations. These are calculated using a detailed modeling of soil, the foundations and the two adjacent structures. An equivalent linear behavior is assumed for the soil by introducing reduced mechanical properties consistent with the level of ground shaking for the free-field soil. Then a distinctive soil zone (the near-field soil) is recognized in the vicinity of the foundations where the peak shear strain under the combined effect of a severe earthquake and the presence of structures is much larger than the strain threshold up to which the soil can be modeled as an equivalent linear medium. It is shown that it is still possible to use an equivalent linear behavior for the near-field soil if its shear modulus is further reduced with a factor depending on the dynamic properties of the adjacent structures, the near-field soil, and the design earthquake. Variations of the dynamic responses of different adjacent structures with their clear distances are also discussed.

1. Introduction

The occurrence of exchange of vibrational energy between adjacent structures through soil is now an established fact confirmed by many theoretical and experimental studies [1–21]. Wang and Schmid [1] analyzed the harmonic response of adjacent structures on flexible bases using a combined procedure of finite and boundary elements methods (FEM–BEM). They concluded that the adjacent structures' responses were functions of the clear distance and the natural frequencies of the system. Imamura et al. [2] calculated the seismic response of a nuclear building including SSSI using three different methods. They observed that the response characteristics of a reactor building can be influenced by existence of a heavy adjacent building. Huang [3] analyzed a three dimensional system consisting of rigid square foundations resting on a homogeneous isotropic linearly elastic halfspace using a time-domain BEM procedure. It was shown that at close clear distances, adjacency results in increased natural frequencies of the system. Similar findings have been reported in other works like those of Mulliken [4] and Mulliken and Karabalis [5]. In the work of Qian and Beskos [6] dynamic interaction of massless adjacent foundations resting on an elastic halfspace was investigated and the results of analysis were compared to the ones derived using ATC-3 regulations. They showed that adjacency of foundations could not be ignored at all frequencies. Subsequently, the same authors utilized the boundary element method to study three dimensional response of a system of two rigid square foundations on the surface of a halfspace under harmonic waves [7]. Their study illustrated that the adjacent response differs from the case of a single foundation as a function of type, angle of incidence and frequency of propagation of the incoming waves, and distance between and mass of the foundations.

A discretized model consisting of frequency-independent springs, dashpots and lumped masses was developed by Mulliken and Karabalis [8] to determine the response of adjacent surface foundations. They used a regression analysis based on least square analysis of the exact and predicted maximum responses. Behnamfar and Sugimura studied a wide range of buildings and compared their responses for the single and adjacent cases [9]. Their study showed that for closer structures, the resonance frequency increases while the seismic response can increase or decrease case by case. Savidis et al. [10] utilized the substructure method and lumped mass modeling of the adjacent structures to conclude that the structures' seismic response was strongly affected by the properties of the soil between the foundations. In another research work, Lehmann and Antes [11] investigated the response of two multi-story buildings on rigid foundations and presented a hybrid FEM-BEM procedure for the analysis. They observed a decreased vertical response because of the adjacency.

* Corresponding author.
E-mail address: farhad@cc.iut.ac.ir (F. Behnamfar).

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In another work, two adjacent structures were modeled on a flexible soil for determining their natural frequencies [12]. It was shown that the boldest effect of adjacency was on the frequencies corresponding to the horizontal and rotational motions of the foundations. Also, it was observed that for clear distances up to half of the plan dimension of the larger structure, the effects of adjacency were important. Xu et al. [13] complemented numerical studies of nuclear structures with accomplishing a number of experiments on reactor–reactor and reactor–turbine structures. Using an equivalent linear modeling of the soil, they observed that in both cases the resonance frequency decreased. The site–city interaction phenomenon was studied by Kham et al. [14]. Two-dimensional BEM models were analyzed under vertical propagation of Ricker SH waves and effects of parameters such as buildings congestion in urban areas and their natural frequencies were investigated for linear soils. A site–city resonance was observed when natural frequencies of soil and the buildings were similar. For adjacent buildings, a decreased maximum response was reported.

Padrón et al. [15] analyzed nearby piled buildings under seismic motions by modeling piles and superstructures with finite elements and soil with the BEM. They observed that the adjacency effects were more pronounced for similar buildings and were strongly affected by the separation distance. Because of the large volume of a structure–soil–structure interaction (SSSI) problem, its modeling is usually implemented with simplistic assumptions, like modeling the structures only with their masses, or as a single-degree-of-freedom (SDF) system. For instance, Ghergu and Lonescu modeled each of the two adjacent structures as an SDF system and calculated the seismic responses [16]. A linear model in the absence of structures was considered for the soil and the effect of structural vibrations on the mechanical characteristics of the supporting soil was disregarded. In a parametric study on the effects of soil–structure interaction (SSI) and SSSI on the response of structures resting on deep foundations, Clouteau et al. [17] utilized FEM and BEM to analyze the soil–structure system. The effects of the adjacency on the impedance functions of foundations and the structural response were determined. Also, Alexander et al. [18] studied the effects of geometrical characteristics of buildings, clear distance, and soil type on the seismic response of adjacent structures using simple discretized models for the buildings and a rotational spring for modeling of soil flexibility.

Yue et al. [19] investigated effects of SSSI on the seismic response of two heavy structures of a nuclear station located adjacent to each other and resting on large embedded foundations. The model consisted of a reactor building including its exterior shield and an adjacent turbine resting on a layered flexible soil profile down to the bedrock. The soil modeled as an equivalent linear medium. They concluded that SSSI was not a decisive factor in the responses. The adjacency problem was also examined by Aldaikh et al. [20] using numerical analysis and shake table tests. It was shown that at close distances, response of the shorter structure was considerably affected by the vibrations of the taller building. Two centrifugal tests were carried out by Trombetta et al. [21] to assess the SSI and SSSI effects on ductility demands of inelastic structures resting on separate mat foundations. While the real structures were 10 by 11 m in plan and 10 and 20 m tall in one or two stories, the experimental models were 55 times smaller. The test results proved that whenever the clear distance was small value, adjacency had a considerable effect on the ductility demand.

The sparseness of the works on SSSI shows the persisting need to evaluate the dynamic response of a building in the vicinity of neighboring buildings on flexible soils. Especially, the soil modeling just below the structures seems to need more attention. In most of the previous research works only the soil (Refs. [13,19]) or the structure (Ref. [21]) has been assumed to behave nonlinearly and the inelastic action has been ignored in the other part of the system, or the nonlinear behavior was not accounted for entirely (Refs. [1–12,14–18,20]). It is the intention of the current study to include nonlinearity in both parts of the problem. The main goal is extending the near-field procedure for SSI problems, presented in a previous work by the same authors [22], to SSSI systems. In this work, the soil zone around the foundations where soil is highly nonlinear is modeled as an equivalent linear zone by adjusting its properties as an extra reduction of the shear modulus of soil in excess of what is done in the well known equivalent linear method (ELM). Also, seismic responses of different adjacent nonlinear structures on flexible soils are calculated and discussed.

2. The structural systems designed

Three buildings having 10, 15 and 30 stories are considered for different cases of adjacency. All the story heights are equal to 3 m. Therefore, the buildings are medium to high-rise structures. The buildings have a common plan with four bays of 5 m length in each of their two directions. The site is located in a high seismicity region on a type D (soft) soil profile [23]. The fixed-base 3D special steel moment resisting frames have been designed based on AISC-2005 [24]. The gravitational loads are $DL = 7.60\ \text{kN/m}^2$ and $LL = 2.00\ \text{kN/m}^2$, with DL for dead load and LL for live load. The diaphragms are RC slabs 0.15–0.25 m thick, with the thicker slabs for the taller buildings, and are assumed to be rigid in plane. The structural sections used for the buildings are summarized in Table 1. The fundamental periods of the fixed-base 10, 15 and 30-story buildings are 2.03, 3.07 and 4.06 s, respectively.

The 10-storey building is founded on a mat foundation with dimensions 21 m × 21 m in plan. For each taller building, a pile group foundation system is utilized. 16 and 25 piles with a center-to-center distance of 5 m are used for the 15 and 30-story buildings, respectively. The pile length and the pile cap thickness are equal to 20 m and 1 m, respectively, while the pile diameters are 0.4 and 0.8 m for the same buildings.

3. The geotechnical considerations

Two different sand and clay soil profiles are considered for the dynamic analysis. Profile 1 is a 25 m thick two-layer sand on the bedrock. Profile 2 consists of three clay layers with a total depth of 45 m on the bedrock. The properties of the soil profiles are presented in Table 2.

The effective values of the shear modulus G and the damping ratio ξ are taken into account for each soil layer. The former is a reduced shear modulus and the latter is an increased damping ratio varied as functions of the increasing shear strains in earthquake when doing a linear free-field dynamic analysis of site with SHAKE2000 [25]. Variation of the shear modulus and damping ratio of soil with shear strain for sand and clay soils is shown in Fig. 1.

Although the assumed soil layering may look to be a specific example, Fig. 2 shows that the site is general enough for the

Table 1
The typical sections of the studied buildings (units in mm, IPE*a* is an I section, *a* mm deep).

No. of stories	Beam sections	Column sections
10	IPE 300, 330 & 360	Box 260 × 20, 280 × 20 & 300 × 20
15	IPE 300, 330, 360	Box 180 × 20, 240 × 20, 300 × 20 & 340 × 20
30	IPE 300, 330, 360 2IPE 330, 2IPE 360	Box 280 × 40, 320 × 40, 340 × 20, 360 × 40 & 380 × 40