Soil Dynamics and Earthquake Engineering 78 (2015) 46–60

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Dynamic response of structures subjected to pounding and structure–soil–structure interaction

B. Madani [a], F. Behnamfar [a,*], H. Tajmir Riahi [b]

[a] Isfahan University of Technology, Esfahan 8415683111, Iran
[b] University of Isfahan, Esfahan 8174673441, Iran

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form
29 June 2015
Accepted 6 July 2015
Available online 1 August 2015

Keywords:
Pounding
Structure–soil–structure interaction
Seismic response
Steel structure

ABSTRACT

During strong earthquakes, adjacent structures with non-sufficient clear distances collide with each other. In addition to such a pounding, cross interaction of adjacent structures through soil can exchange the vibration energy between buildings and make the problem even more complex. In this paper, effects of both of the mentioned phenomena on the inelastic response of selected steel structures are studied. Number of stories varied between 3 and 12 and different clear distances up to the seismic codes prescribed value are considered. The pounding element is modeled within Opensees. A coupled model of springs and dashpots is utilized for through-the-soil interaction of the adjacent structures, for two types of soft soils. The pounding force, relative displacements of stories, story shears, and plastic hinge rotations are compared for different conditions as the maximum responses averaged between seven consistent earthquakes. As a result, simultaneous effects of pounding and structure–soil–structure interaction are discussed.

1. Introduction

Neighboring structures resting on soft soil can alter the dynamic responses of each other through two different phenomena. First, flexible soils are affected by the structural response and transmit the vibration energy between adjacent buildings. This is called structure–soil–structure interaction, or SSSI. Second, if the clear distance is not enough, neighboring buildings will collide during dynamic response under large earthquakes that is called pounding. There have been many studies on the separate effects of the above events. In comparison, only a relatively small number of works can be found in which the simultaneous effects of pounding and SSSI are accounted for. Selected works are reviewed in the following in this regard.

Rahman et al. studied two adjacent 6 and 12-story reinforced concrete (RC) buildings in a system of a linear underlying soil and nonlinear structures using the software called Ruaumoko [1]. To model the soil, they used the mass-damper-spring system proposed by Mulliken and Karabalis [2] under the perimeter columns for modeling of SSSI. Moreover, pounding elements were included at all floor levels. They reported the most prominent effect of soil flexibility as being increase of the pounding force at all levels, especially at the roof of the shorter building. Behnamfar et al. [3] studied two single degree of freedom (SDF) systems resting on soft soils. Again the mass-damper-spring system of Mulliken and Karabalis was utilized to model the soil-structure interaction (SSI) and SSSI. They concluded that SSSI first of all changes the frequencies of rocking motions of the system to larger values. Also, they observed that whenever the clear distance was smaller than 2.5 times the foundation width, the SSSI had important effects on the structural responses.

Yahyai et al. [4] investigated the SSI and SSSI effects on two adjacent 32-story steel structures using the Ansys software. The soil medium included three different cases of soft clay, intermediate sand-gravel, and compact sand-gravel. They studied only the SSSI phenomenon and did not account for pounding. It was observed that SSI resulted in a period lengthening of buildings and augmentation of their damping ratios, with these effects being more highlighted in taller buildings and on softer soils. In addition, SSSI resulted in increase of the base shear and roof displacement compared to the SSI as a function of the clear distance. Cole et al. [5] reported the flexibility of soil to be responsible for increase of lateral responses of structures and more extensive pounding between adjacent buildings. They proposed a period lengthening relation for structures on flexible soils as a way for inclusion of larger displacements in structural models. Mahmoud et al. [6] studied pounding between buildings including flexibility of soil.

---

[*] Corresponding author.
E-mail addresses: madani.bahareh@yahoo.com (B. Madani), farhad@cc.iut.ac.ir (F. Behnamfar), tajmir@eng.ui.ac.ir (H. Tajmir Riahi).

http://dx.doi.org/10.1016/j.soildyn.2015.07.002
0267-7261/

They used a stick model (shear building) for each structure with lumped masses being located at certain elevations. For modeling of soil, they made use of suitable springs and dampers for translational and rotational degrees of freedom (DOF's). It was concluded that extra sway and rocking induced by foundation movements can have considerable effects on structural responses, especially those of lighter and more flexible structures. Flexibility of soil in their study resulted in a larger number of pounding incidents at higher levels and its reduction in lower floors.

Naserkhaki et al. [7] investigated two multi degree of freedom (MDF) models including lumped masses, viscous dampers, and linear springs. Appropriate springs and dampers were used for taking into account the SSI and SSSI. It was reported that period of the pounding system was always located between the periods of the two buildings at their single (no adjacency) condition being nearer to the more flexible taller building. For the pounding, it was concluded that it reduced displacements and increased story shears of the softer building and increased both above responses in the stiffer structure, compared to when the base is taken to be rigid. Barbato and Tubaldi [8] used a probabilistic approach to determine the appropriate clear distance between adjacent buildings. Their method makes it possible to calculate the distance based on a certain probability of pounding. They studied linear and nonlinear structures and concluded that certain building codes underestimate the clear distance. Efraimiadou et al. [9,10] studied the effect of adjacency configuration and type of the ground motion on pounding by investigating two-dimensionally two adjacent 5-story and two adjacent 8-story buildings at 9 different cases of adjacency. The base of the buildings was assumed to be rigid. They concluded that in all cases the detrimental effects of pounding were more extensive than its advantages with this fact being bolder in the taller building. Also, they studied the effects of successive earthquakes by applying the next ground motion to the adjacent buildings already having permanent plastic deformations due to the previous strong motion. It was concluded that the code-based clear distance was not enough to suppress the negative effects of pounding in this case. Bi and Hao [11] performed numerical simulations of pounding damage between bridge girders and between bridge girder and the corresponding abutment of a two-span simply-supported bridge to spatially varying ground motions based on a 3D finite element model. The dislocation and unseating potentials of the bridge were also included. Khatiwada et al. [12] performed a numerical and experimental study on two adjacent steel frames with a zero clear distance. One of the frames was used as the reference while stiffness and mass of the other one were changed in 8 cases. The results were presented as lateral displacements of the reference frame normalized to those of a similar single frame. Varying the pounding element in the numerical model, they concluded that the viscoelastic element yielded results closer to the experimental values. They introduced the restitution factor, in place of stiffness of the pounding element, as a key factor affecting the response and recommended its value to be taken as 0.4.

Pratesi et al. [13] analyzed pounding between a modern heritage R/C bell tower constructed in the early 1960 s with its enclosing church building. They devised a multi-link viscoelastic finite element contact model. According to the non-linear dynamic analysis of the system, pounding affected the seismic response of the two buildings under the design earthquake and unsafe stresses developed in the columns of the tower when the system was subjected to the maximum considered earthquake. Skrekas et al. [14] considered a case study of a reinforced concrete EC8-compliant, torsionally sensitive, 7-story corner building constructed within a block, in bi-lateral contact with two existing R/C 5-story structures with same height floors. A non-linear local plasticity numerical model was developed and a series of non-linear time-history analyses was performed to assess the pounding effects. Seismic pounding was shown to distort the structural response of the entire block but on average it had a decreasing effect on the inelastic demands at the lower floors of the 7-story building. Pawar and Murnal [15] studied the pounding effect between adjacent blocks of unsymmetrical buildings separated by seismic gap considering SSI. They observed that SSI had both beneficial and detrimental effects on the seismic response and it increased number of impacts between the buildings studied. Raheem [16] studied two nonlinear 8 and 13-story adjacent buildings for different clear distances under 9 different seismic motions. Maximum displacement, story shear and acceleration at the 8th floor of both buildings were calculated. It was shown that pounding could result in increasing shear and acceleration responses while ground motion characteristics were introduced as responsible for larger drifts. Use of energy absorbers was suggested and it was shown to be effective in reducing pounding force and floor accelerations.

Review of the literature as above clearly shows that state of knowledge about SSSI with pounding is still at its early situation. A dire need exists for nonlinear modeling of adjacent structures and their underlying soil. Nonlinear dynamic response to a suit of consistent ground motions should be sought. These are the features of the present work.

2. Procedures for modeling of pounding

Several procedures are available for modeling of pounding. In all of these methods, stiffness of the pounding element must be introduced. The value of the stiffness depends on the impacting materials and the geometry of the pounding surface and there is no widely used unique relation for its computation [12]. Most of researchers resort to experimental methods for this purpose. The more important procedures are as follows.

2.1. The available procedures

The linear elastic model is based on a linear elastic impact [17]. This model utilizes a spring with a large stiffness that is only activated when the instantaneous clear distance becomes zero. One of the suggested approaches is to calculate the pounding element's stiffness as the sum of axial stiffnesses of the two adjacent floors [18]. The model is shown in Fig. 1.

The above model is not able to include the energy loss during impact that is a serious shortcoming of this model.

The linear viscoelastic model called also the Kelvin model, is based on an impact involving a viscous damper and a linear spring [17]. It is shown in Fig. 2.

The values of damping coefficient c, spring stiffness k, damping ratio ξ, restitution factor e, and adjacent masses m_1 and m_2 are related through Eqs. (1) and (2)

$$c = 2\xi\sqrt{k\frac{m_1 m_2}{m_1 + m_2}} \qquad (1)$$

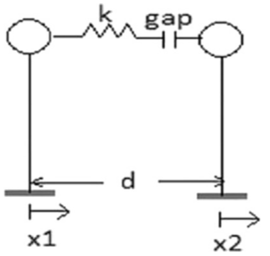

Fig. 1. The linear elastic pounding model.