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Effects of mutual cross interaction and pounding on nonlinear seismic response of adjacent buildings

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ABSTRACT

Earthquake-induced pounding between inadequately separated structures may cause considerable damage. The main reason of occurrence of this phenomenon is out-of-phase vibration of adjacent structures. As buildings in populated areas are usually closely located, pounding can be an important phenomenon when investigating their seismic response.

In many researches on pounding, energy transfer through the underlying soil between the adjacent buildings which is called structure-soil-structure interaction is omitted. In this paper, this cross-interaction phenomenon is studied for sample buildings. Different models for simulation of impact between adjacent buildings are examined and it is shown that the gap model of Opensees results in more rational response values. Several cases of the clear distance and heights of buildings are considered. The underlying soil is modelled with spring-damper coefficients resulting in consideration of both structure-soil-structure interaction and pounding in a single analysis model. Seven consistent earthquake records are selected for nonlinear time history analysis of the system. The results are shown and compared as variation of structures nonlinear responses (story drift, shear) and pounding forces due to the cross interaction. Effects of soil flexibility are highlighted when it results in a larger response in conjunction with pounding.

INTRODUCTION

Increase of population and living areas being condensely located have resulted in buildings spaced too closely apart in densely inhabited areas. For taller buildings, such proximity increases the possibility of pounding between adjacent buildings. The energy exchange between pounding structures can happen through another route too, i.e., the soil beneath the buildings. The latter phenomenon is called cross interaction between adjacent buildings.

Study of pounding has been the subject of many research works in the last few decades, especially after the 1985 Mexico City earthquake exhibited many instants of the same phenomenon. In the following a number of those tasks are listed.

Desroches and Muthukumar (2004) used several types of contact elements with/without dampers behaving linearly or nonlinearly, to study pounding of two single-degree-of-freedom (SDF) oscillators. Jankowski (2006) introduced the pounding force spectrum as a tool for design of adjacent buildings for the pounding force. Such a spectrum is a three-dimensional (3D) representation of the maximum pounding force as a function of natural periods of the two buildings. Mostafa and Mahmood (2012) studied two elasto-plastic SDF systems and derived their damage indices as a global damage indicator for different clear distances. Lin and Weng (2001) evaluated the probability of pounding

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between two MDF adjacent buildings. They studied 36 cases of adjacency and concluded that the period ratio of the two buildings was the prime factor in determining the pounding chance. Carr et al. (2001) studied two nonlinear 6 and 12-story reinforced concrete (RC) buildings resting on elastic soils. For modeling of soil they utilized a lumped parameter system of mass-spring-damper under all columns proposed by Mulliken and Karabalis (1998) and accounted for pounding elements at all floors. According to their results, the most important effect of consideration of soil-structure-interaction (SSI) as above was lengthening of the period of the oscillating structure. Kermani et al. (2003) investigated two adjacent SDF systems resting on a flexible soil. They reported the prime effect of proximity of structures to be increase of the frequency of rocking motion of buildings. Jankowski et al. (2012) embarked on pounding of two 3-story adjacent buildings on a flexible base and concluded that including the sway and rocking motion of base affected the structural response especially for lighter and more flexible buildings.

In this study, considering the gap in the related research, distribution of seismic responses through building members is studied for adjacent buildings behaving nonlinearly on nonlinear flexible soils.

MODELING OF THE ADJACENT BUILDINGS

Steel structures being 3 and 5 stories in elevation are considered. They are designed as 3D moment resisting systems. Then an interior 2D frame is picked up for nonlinear dynamic analysis. Pairs of 3 and 5-story frames with both fixed and flexible bases and with three different clear distances are modeled for the same purpose in Opensees. A simple schematic of such a system is shown in Fig.1. Story heights are equally 3.4 m.

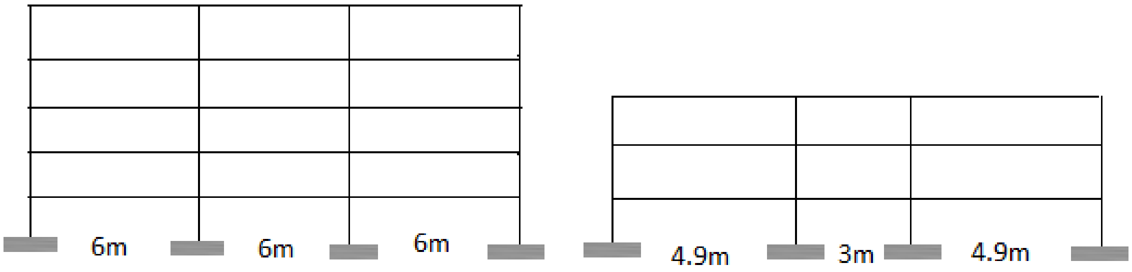

Fig. 1. Schematic of the adjacent buildings under study

Different approaches are available for modeling of beams and columns in Opensees. Out of which, in this study the concentrated plasticity model is taken for nonlinear analysis of frames. The pounding occurrence and its effects are evaluated for three different clear distances: zero (contacting buildings), half of the code prescribed separation distance (SD), and the full code SD. The latter value is calculated to be about 14 cm.

THE POUNDING ELEMENT

In this study, a pounding element is considered at each level of the system of Fig.1 to simulate the pounding force. It consists of a linear viscoelastic member embedded in Opensees for the same purpose. This element is shown in Fig. 2 as a spring-damper-gap system connecting two SDF masses.

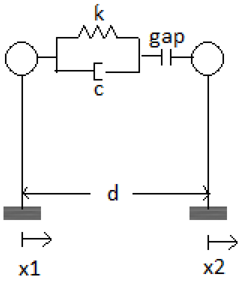

Fig. 2 . the pounding element

The characteristics of the pounding element are the damping C and stiffness K. The damping value is calculated as follows (Desroches and Muthukumar, 2004., Anagnostopoulos, 1988) :

$$c = 2\xi\sqrt{k\frac{m_1 m_2}{m_1+m_2}} \tag{1}$$

$$\xi = -\frac{\ln(e)}{\sqrt{\pi^2+(\ln(e))^2}} \tag{2}$$

in which ξ is the damping ratio calculated based on the restitution factor e, and m_1 and m_2 are masses of structures 1 and 2. For the stiffness, a large value is appropriate to account for in-plane stiffness of (concrete) floors. A value of 1e11 proves to be suitable considering numerical stability issues. The restitution factor is equal to 0.65 (Desroches and Muthukumar, 2004., Anagnostopoulos, 1988).

MODELING OF SOIL

In addition to the fixed base case, a type D (soft to intermediate) sandy soil having a shear wave velocity V_s equal to 200 m/s is taken into account for the flexible base analysis. The SSI is modeled using the theory of beam on nonlinear Winkler foundation as is provided in Opensees.

Since the strip foundations designed for both buildings prove to be flexible with regard to their supporting soil, vertical springs with a uniform distribution are attributed to the bottom of the foundations. The horizontal stiffness is modeled as a concentrated spring. This is shown in Fig. 3. The values of the spring stiffnesses in the horizontal (x) and vertical (z) directions, according to Gazetas (1991) are as follows:

$$K_z = \frac{1.3G}{B(1-\upsilon)} \tag{3}$$

$$K_x = \frac{GL}{2-\nu}\left[2+2.5\left(\frac{B}{L}\right)^{0.85}\right] + \frac{GL}{0.75-\upsilon}\left[0.1\left(1-\frac{B}{L}\right)\right] \tag{4}$$

in which G is the effective shear modules, L and B are length and width of the strip foundation, respectively, and ν is the Poisson's ratio of soil.

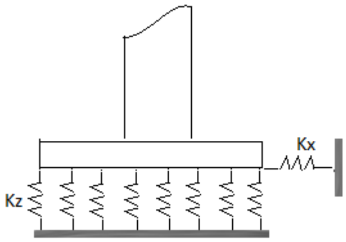

Fig. 3 . Modeling of the foundation as a beam on nonlinear Winkler foundation.

The above stiffness values are assigned to springs with Qzsimple and Tzsimple constitutive relations. The latter relations correspond to the vertical and horizontal load-displacement behavior in soil with no-tension and nonlinear compression characteristics (Harden et al., 2005).

For modeling of cross-interaction, pairs of springs and dampers are used in horizontal, vertical and rotational direction as suggested by Mulliken and Karabalis (1998). The characteristics of such lumped parameters are given in Table 1. As observed, constants ψ and Γ are utilized in the above table. Formulas for the constants are presented in Table 2. They are functions of the clear distance and the foundation's width.

Table 1. Spring stiffness and damping coefficients for coupling between adjacent foundations.

In Table 1, G, ν and V_s are the effective shear modules, the Poisson's ratio and the shear wave velocity of soil, respectively, and a is the half-width of the square foundation.

Table 2. Constants for calculation of the coupling soil springs and dampers.

S	×	3	+	
D				

In Table 2, d is the clear distance between the foundations.

THE ANALYSIS RESULTS

The pair of the adjacent buildings of Fig. 1 is analyzed as inelastic frames for the mentioned three clear distances under 7 consistent earthquake records. The ground motions are taken from the PEER strong motion database with the common characteristics of the magnitude being in the range of 6.5-7.5 and distance from fault being in the range of 20-50 km. They are then scaled according to ASCE7-10. The selected records are coded as NGA 1180, 1183, 1204, 1238, 1246, 1483, and 1537 in the PEEAR’s database.

To summarize the results and present them in a more readable way, only the average of maximum responses are presented. The structural responses to be exhibited are maximum story shears and drifts averaged between earthquakes. Also the maximum pounding force at each level is shown, if ever pounding happens at that level.

VARIATION OF THE POUNDING FORCE

The maximum pounding force is shown in Figs. 4 & 5 for the mentioned distances distinguished by $d = 0, 0.5, 1$. The horizontal axis shows the story number (N) and the vertical axis represents the maximum pounding force at each level averaged between the records.

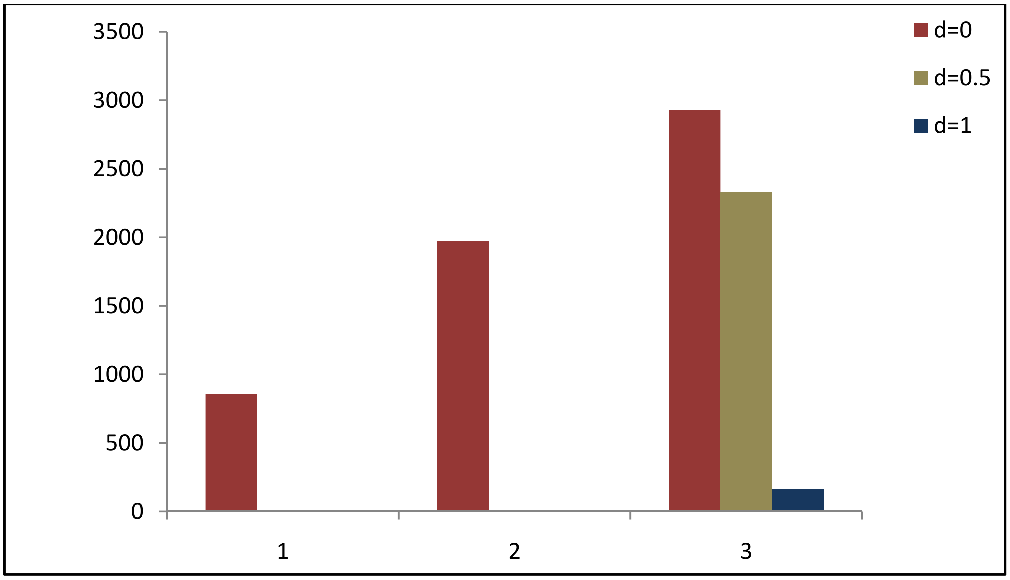

Fig. 4. Maximum pounding force at each level for different clear distances for the fixed base building.

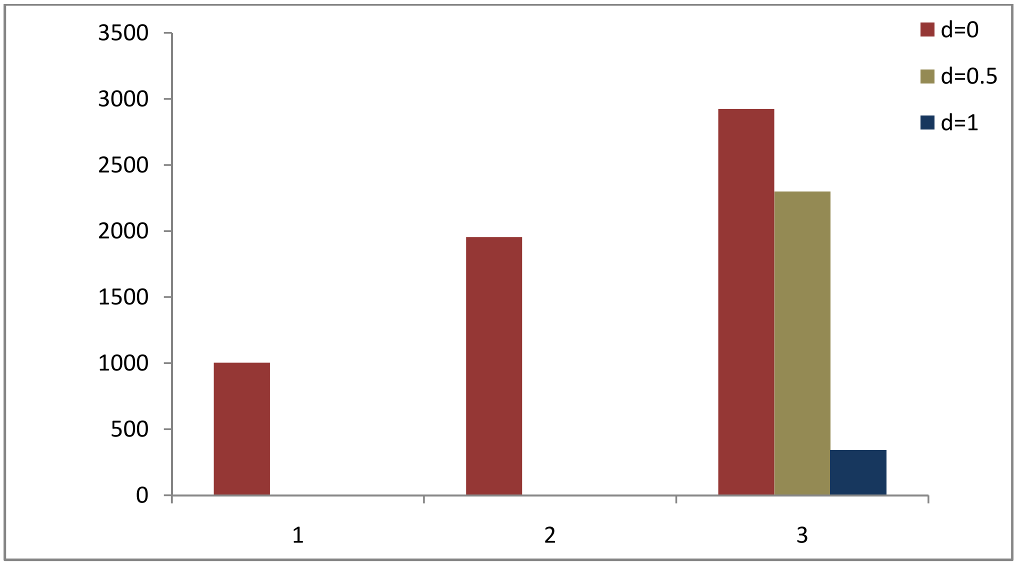

Fig. 5. Maximum pounding force at each level for different clear distances for the flexible base building.

Figs. 4 & 5 show that accommodating the building with the minimum code-prescribed separation distance results in no pounding at all. On the other hand, reduction of the clear distance always results in augmentation of the pounding force at all floor levels, such that for $d = 0.5$, the pounding force lies between the forces corresponding to the two extreme cases. Therefore, at all floors, the pounding force increases uniformly with decreasing distances. Also, flexibility of soil has resulted in smaller pounding forces in many cases.

VARIATION OF THE STORY DISPLACEMENT

The story displacements (U) are shown for different clear distances in Figs. 6 to 9.

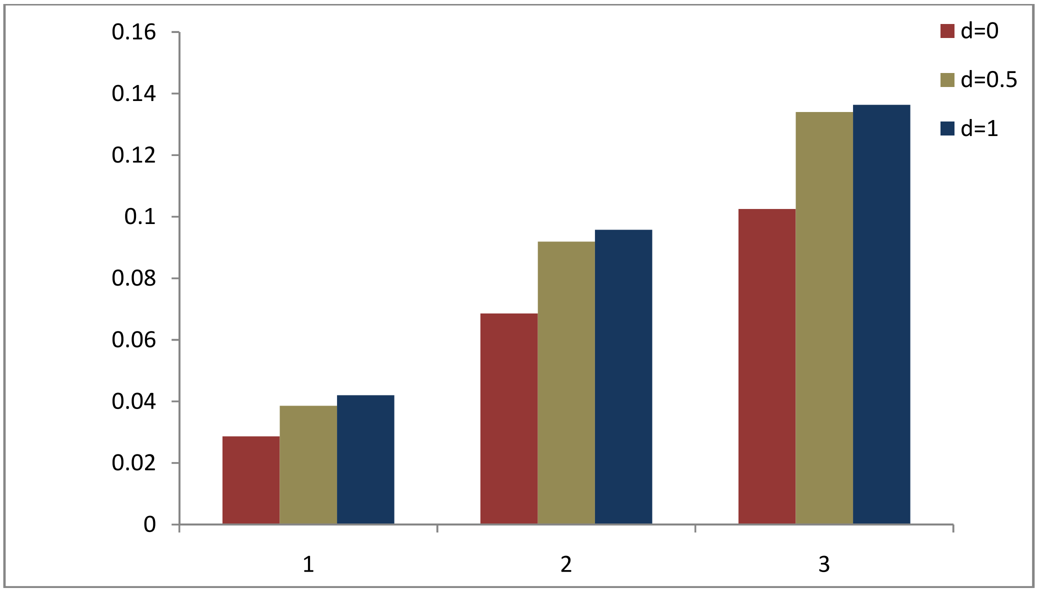

Fig. 6. Maximum story displacements for different distances, for the 3-story building with a fixed base.

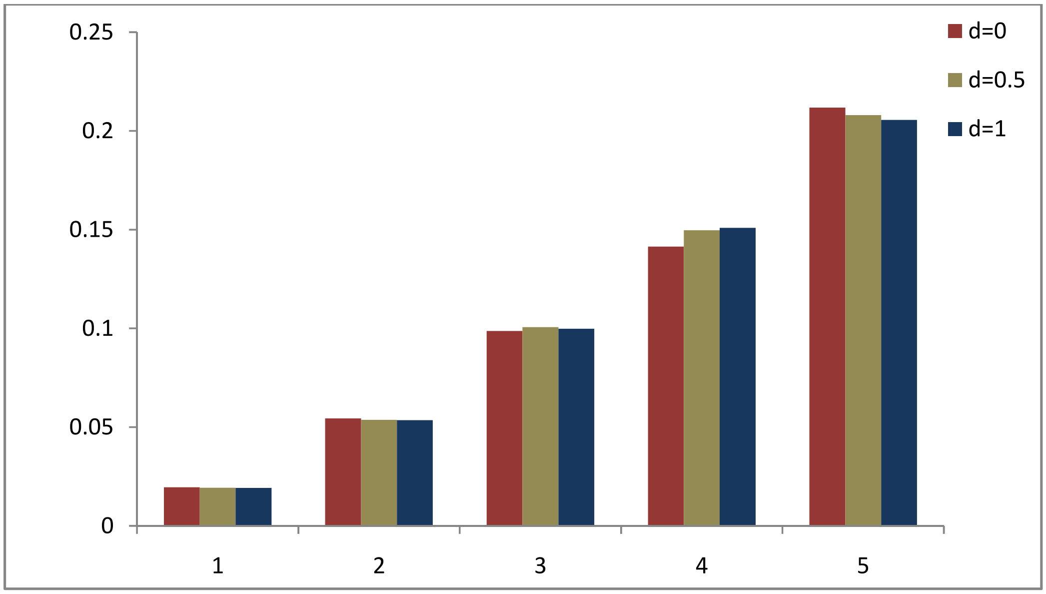

Fig. 7. Maximum story displacements for different distances, for the 5-story building with a fixed base.

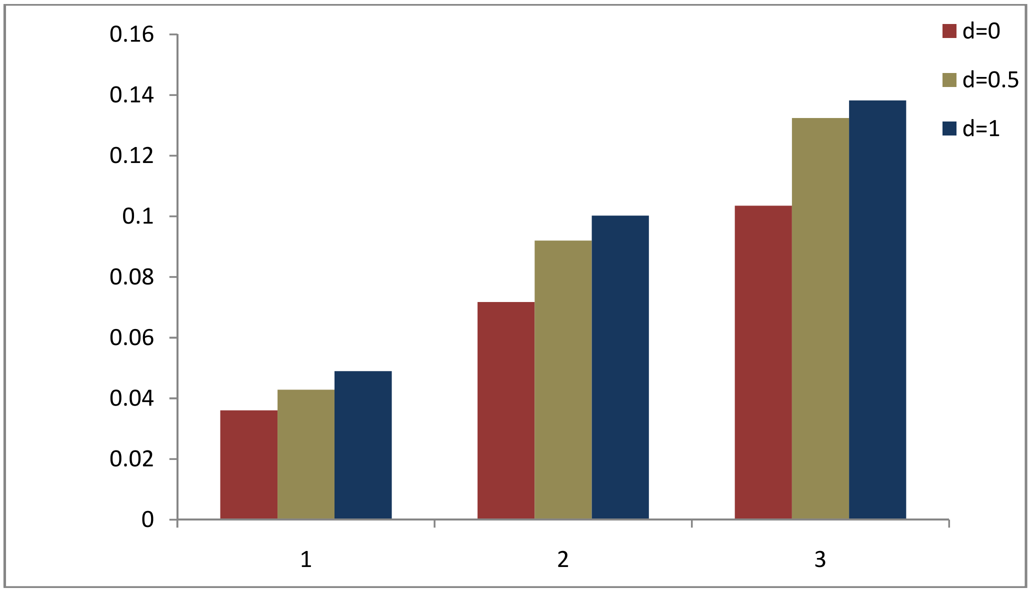

Fig. 8. Maximum story displacements for different distances, for the 3-story building with a flexible base.

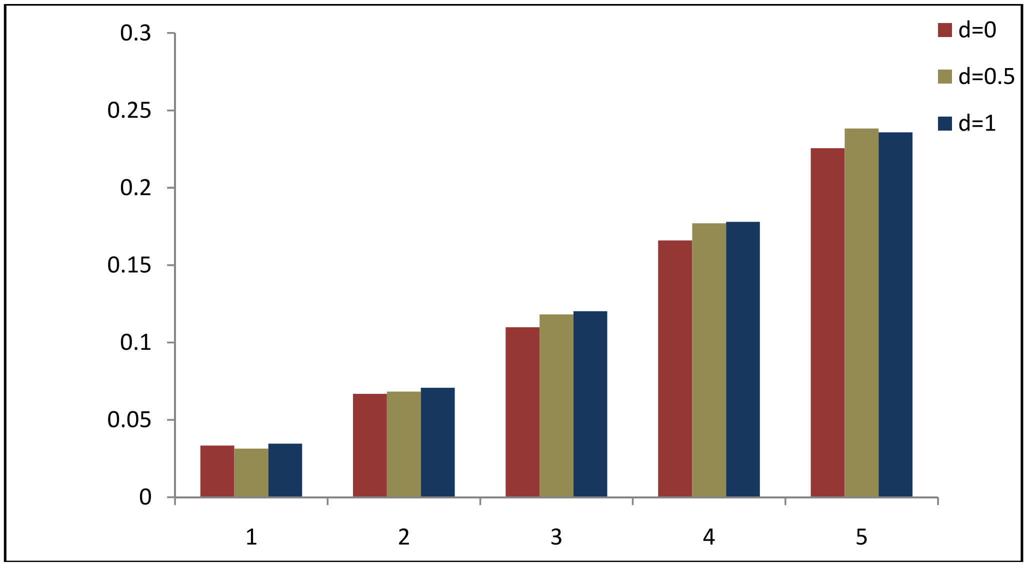

Fig. 9. Maximum story displacements for different distances, for the 5-story building with a flexible base.

As seen, in the shorter building, pounding results in smaller displacement responses. It is as much as a 31% and 28% reduction for the fixed base and flexible base cases, respectively. This effect is less highlighted in the taller building and the maximum reductions are only 7% and 6% for the fixed base and flexible base cases, respectively. On the other hand, flexibility of soil has a detrimental effect as it increases the displacements of the lower third of the building floors.

VARIATION OF THE STORY SHEARS

Resultant of the shear forces at each story is shown in Figs. 10 to 13.

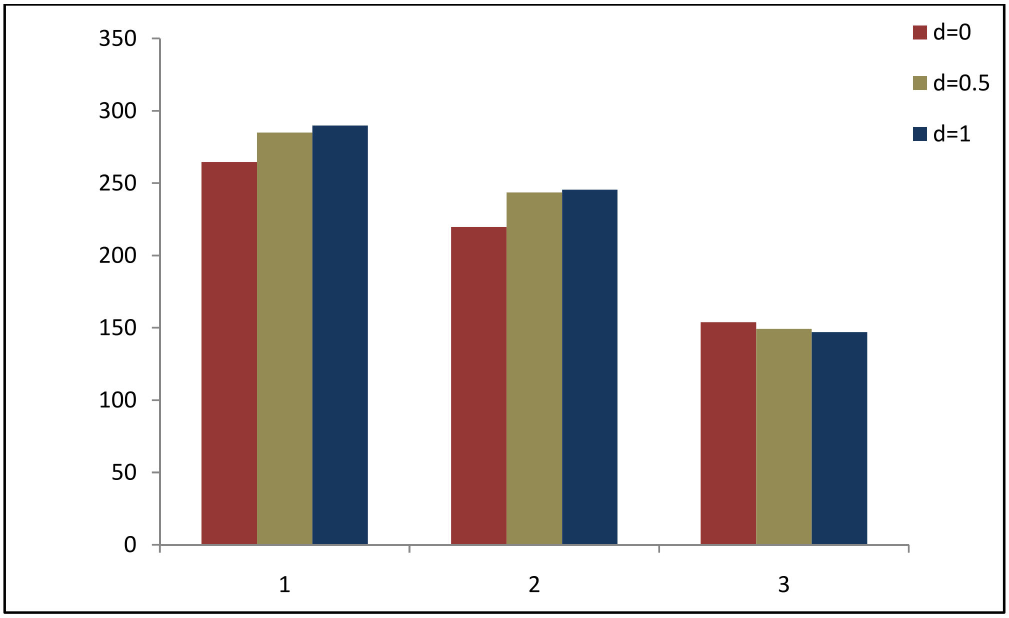

Fig. 10. Story shears of the 3-story building for different clear distances with a fixed base.

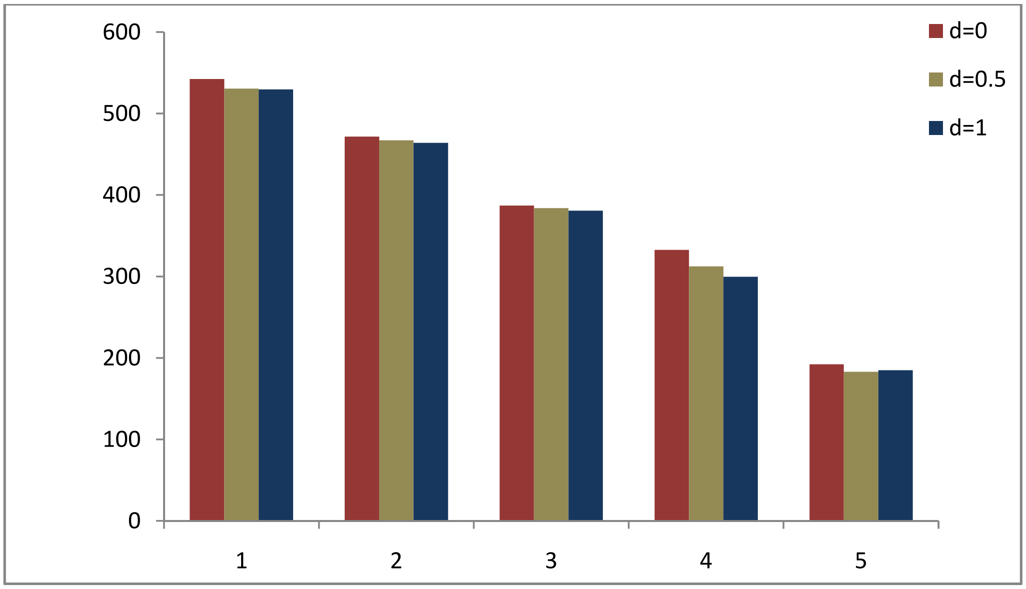

Fig. 11. Story shears of the 5-story building for different clear distances with a fixed base.

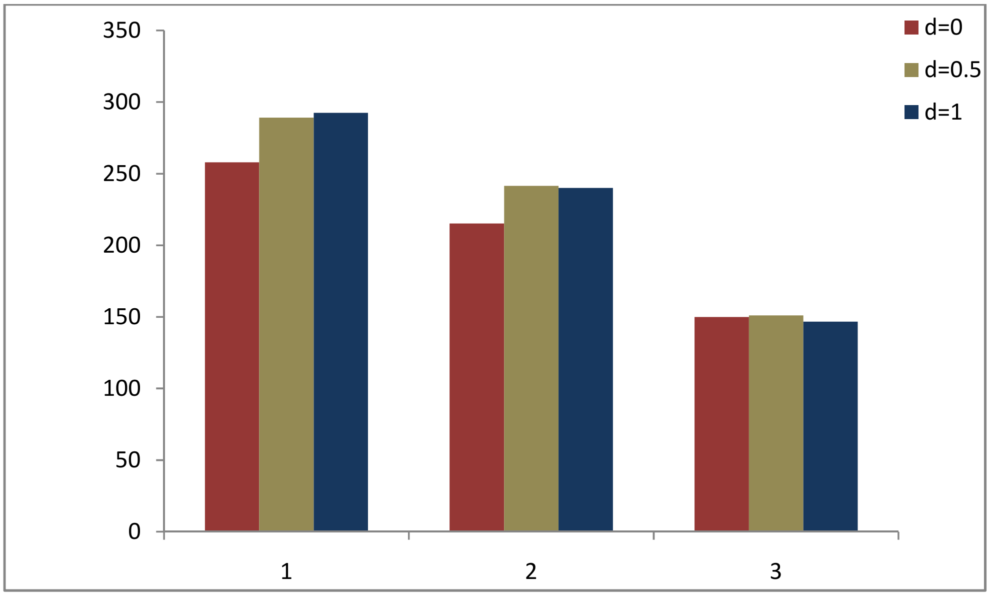

Fig. 12. Story shears of the 3-story building for different clear distances with a flexible base.

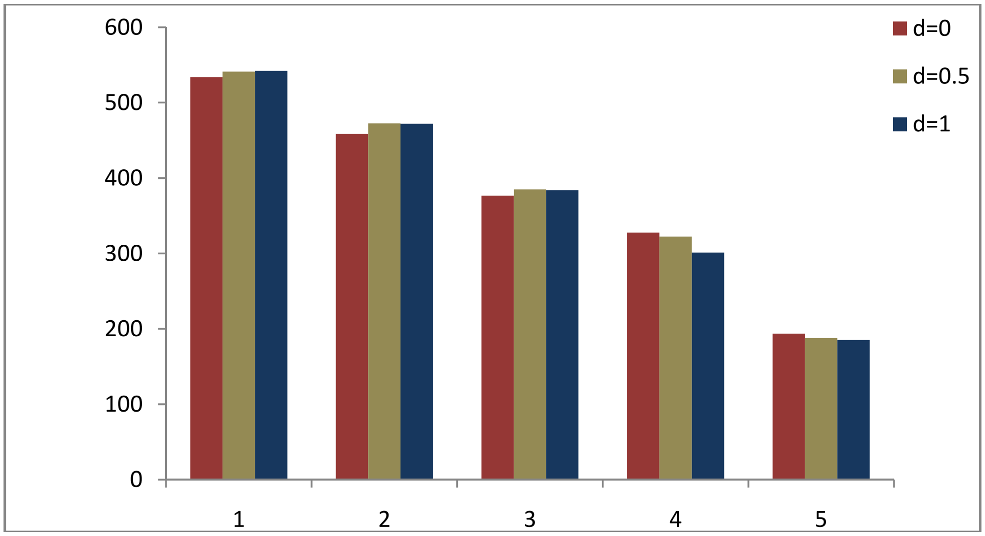

Fig. 13. Story shears of the 5-story building for different clear distances with a flexible base.

Pounding decreases the story shears of the shorter building except of its higher story where the story shear increases slightly (4% and 2% for the fixed base and flexible base cases, respectively). The amount of shear reduction reaches at most to 10% and 11% for the fixed base and flexible base cases, respectively, at the first story. In the taller building, pounding again decreases the story shear up to a level equal to roof level of the shorter building. But for the higher levels, the story shear increases in the taller building up to 9% for both fixed base and flexible base cases. SSI also decreases the story shears in all cases. Maximum reductions of the story shear due to SSI is seen to be 4% for the second floor of the taller building with a clear distance of $d = 0$.

CONCLUSIONS

In this paper pounding between two adjacent buildings resting on flexible bases was investigated. It was shown that the pounding force increases for smaller clear distances. The code-prescribed clear distance was proved to be enough to prevent the buildings from impacting each other for most earthquake cases. The displacement of floors was shown to be a decreasing function of pounding especially in the shorter building. It can increase slightly in the upper floors of the taller building with regard to when no pounding is considered. The flexibility of soil added to the reduction of displacements, while the story shears decreased under the effect of pounding in the shorter building It increased due to the same cause in all stories of the taller building especially those located higher than roof of the shorter building. SSI decreased the story shear in all stories.

REFERENCES

Anagnostopoulos S A (1988) “Pounding of buildings in series during earthquake”, *Earthquake Engineering and Structural Dynamics*, 16: 443-456.

Behnamfar F, Kermani M, Saadatpoor M (2003) "Variation of the natural frequencies of the adjacent buildings resting on flexible soil", *6th International Conference of Civil Engineering, Esfahan.*

Gazetas G (1991) "Formulas and charts for impedances of surface and embedded foundations", *Journal of Geotechnical Engineering* , 117(9).

Harden C W, Hutchinson T, Martin G R, Kutter B L (2005) “Numerical modeling of the nonlinear cyclic response of shallow foundations”, *Pacific Earthquake Engineering Research Center*, Report No. 2005/04, PEER.

Jankowski R. (2006) “Pounding force response spectrum under earthquake excitation”, *Journal of Engineering Structures*, 28: 1149-1161.

Lin J H, Weng C C (2001) “Spectral analysis on pounding probability of adjacent buildings”, *Journal of Engineering Structures*, 23: 768-778.

Mahmoud S, Abd-Elhamed A, Jankowski R (2012) “Earthquake-induced pounding between equal height multi-story buildings considering soil-structure interaction”, *Bulletin of Earthquake Engineering*, 11:1021-1048.

Moustafa A, Mahmoud S (2012) “Damage Assessment of Adjacent Buildings with Fixed Bases under Earthquake Loads”, *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisboa.

Mulliken J S, Karabalis D L (1998) “Discrete model for dynamic through-the-soil coupling of 3D foundations and structures”, *Journal of Earthquake Engineering and Structural Dynamics*, 27: 687-710.

Muthukumar S, Desroches R (2004) “Evaluation of impact models for seismic pounding”, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, No. 235.

Rahman A M, Car A J, Moss P J (2001) “Seismic pounding of a case of adjacent multiple-story buildings of differing total heights considering soil flexibility effects”, *Bulletin of the New Zealand Society for Earthquake Engineering*, 34(1): 40-59.

Iranian Standards and Industrial Research Institute(2006) “Design of Buildings Under Earthquake Loads”, National Standard No. 2800, , Ver. 3.

PEER Ground Motion Database: http://peer.berkeley.edu/peer_ground_motion_database

American Society of Civil Engineers (2010) “Minimum Design Loads for Buildings and Other Structures”, Structural Engineering Institute, ASCE/SEI 7-10.