Incremental dynamic analysis and fragility assessment of buildings with different structural arrangements experiencing earthquake-induced structural pounding

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Abstract

Structural pounding is considered as one of the most critical phenomena occurring during earthquakes. This paper presents the incremental dynamic analysis and fragility assessment of buildings experiencing earthquake-induced pounding. Three 3-D buildings with different number of storeys and under different structural arrangements have been considered. Three pounding scenarios have been taken into account, i.e. pounding between 5-storey and 7-storey buildings, pounding between 5-storey and 9-storey buildings and pounding between 7-storey and 9-storey buildings. The incremental dynamic analysis and fragility assessment has been performed for these three buildings in the three pounding scenarios as well as for the no pounding case. The results of both incremental dynamic analysis and fragility assessment illustrate that pounding can be beneficial and destructive, depending on the structural response and ground motion shift versus time. No clear relation has been observed because pounding is a highly complicated phenomenon.

Keywords: structural pounding; incremental dynamic analysis; fragility assessment; earthquakes; buildings; performance levels

1. Introduction

Structural pounding is defined as repeatedly observed collisions occurring between adjacent structures during earthquakes which is considered as a significant phenomenon [1-3]. It has been experienced in several earthquakes, such as the Mexico earthquake where in 40% of buildings pounding was found, and in 15% of buildings with severe damage or collapse, pounding was visible [4] where in 20-30% of them pounding was the major reason of damage [5]. Pounding was also experienced in 200 out of 500 surveyed buildings in the Loma Prieta earthquake [6]. It was also experienced in Christchurch (New Zealand, 2011) [7] and Gorkha (Nepal, 2015) [8] earthquakes.

Research on earthquake-induced pounding has been conducted for more than three decades (see [9, 10]). Pounding was found to increase the floor peak accelerations, shear forces, and impact forces while the displacement may increase or decrease [11]. The degree of the amplification depends on the dynamic properties (mass, ductility, damping ratio, period, etc.) of colliding buildings. The properties of the ground motion also have a significant effect on the colliding structures [12]. The response of colliding buildings is substantially affected in the direction of pounding and unaffected in the other direction [13]. Crozet et al. [14, 15] also found that the frequency ratio has the

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largest influence on the maximum impact force and ductility demands while the frequency and mass ratios have the largest influence on the impact impulse (mass ratio is predominant for low frequency range).

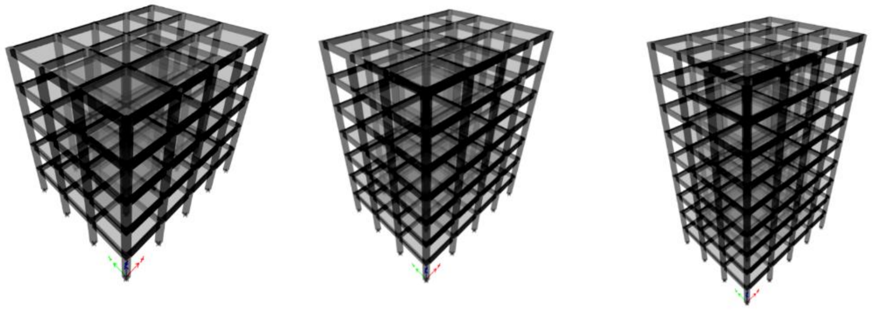
The previously mentioned literature review illustrates that pounding is a substantial phenomenon and leads to severe damages during earthquakes. However, little attention has been paid to the damage state and the performance level of the colliding buildings during earthquakes. Therefore, the aim of this paper is to perform incremental dynamic analysis and fragility assessment of buildings with different structural arrangements experiencing pounding.

2. Incremental dynamic analysis and fragility assessment

The incremental dynamic analysis (IDA) and the fragility assessment method are among the modern methods to evaluate the seismic response of colliding buildings. IDA is a parametric analysis method used to estimate the structural performance of vibrating buildings under certain earthquake record (see [16] for details). It has been widely used in nonlinear dynamic analyses as well as in studying pounding phenomenon (see [17-19] for example). In this paper, the method proposed by Ibrahim and El-Shami (2011) were used to develop the fragility curves [20]. Five different performance levels have been considered by researchers, i.e. the operational performance (OP), immediate occupancy (IO), damage control (DC), life safety (LS), and collapse prevention (CP). The maximum allowable interstorey drifts for each performance level were taken into account based on Xue et al. (2008) [21] recommendations which are 0.5%, 1.0%, 1.5%, 2.0% and 2.5% for the for the OP, IO, DC, LS and CP performance levels, respectively [21].

3. Numerical models of buildings

Three buildings with 5, 7 and 9 storeys have been analysed. All of them have a storey height of 3 m and a width of 16 m in the x-direction and 12 m in the y-direction (the bays are 4×4 m and 3×4 m in x- and y- directions, respectively). The analysis has been performed using ETABS software. The Finite Element (FE) models of these three buildings are shown in Figure 1.



(a) 5-storey building (b) 7-storey building (c) 9-storey building

Fig. 1. FE model of the studied buildings

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Three pounding scenarios have been considered, i.e. pounding between 5-storey and 7-storey buildings (5-7 pounding), pounding between 5-storey and 9-storey buildings (5-9 pounding) and pounding between 7-storey and 9-storey buildings (7-9 pounding). A gap of 4 cm has been provided between these buildings for all the cases. The soil type A (hard rock) defined in the ASCE 7-10 code [22] has been chosen in all cases of both pounding and no pounding cases. The soil type has been considered using the response spectrum concept (see [11, 23], for details). The IDA has been conducted for three earthquake records which are: San Fernando, Loma Prieta, and Imperial Valley (station: Agrarias). Then, the fragility curves of the colliding buildings have been developed based on the IDA curves.

4. IDA

In this section, the average IDA of the IDA curves of the three ground motions are presented in different pounding scenarios and compared with the no pounding case. The average IDA curves for the 5-storey, 7-storey, and 9-storey buildings are presented in Figures 2a, 2b and 2c, respectively, under different pounding scenarios. As it can be seen from Figure 2a, the 5-storey building can sustain a PGA of 0.27g to stay fully operational in the case of no pounding, a PGA of 0.28g in the case of 5-7 pounding and a PGA of 0.3g in the case of 5-9 pounding. Indeed, the 5-storey building can sustain a PGA of 0.53g to be immediately occupied in the case of no pounding, a PGA of 0.55g in the case of 5-7 pounding and a PGA of 0.61g in the case of 5-9 pounding. Moreover, the 5-storey building can sustain a PGA of 1.06g before losing its safety in the case of no pounding, a PGA of 1.08g in the case of 5-7 pounding and a PGA of 1.21g in the case of 5-9 pounding. Also, the 5-storey building can sustain a PGA of 1.33g before collapse in the case of no pounding, a PGA of 1.35g in the case of 5-7 pounding and a PGA of 1.49g in the case of 5-9 pounding. In this case, pounding is considered beneficial to the colliding buildings as the 5-storey building is found to be capable to sustain higher PGAs before reaching certain performance level in the case of pounding than in the case of no pounding. This is referred to the fact that the pounding blocks the movement of vibrating buildings. Furthermore, as it can be seen from Figure 2b, the 7-storey building can sustain a PGA of 0.25g to stay fully operational in the case of no pounding and a PGA of 0.23g in the case of 7-9 pounding. Indeed, the 7-storey building can sustain a PGA of 0.51g to be immediately occupied in the case of no pounding and a PGA of 0.48g in the case of 7-9 pounding. Moreover, the 7-storey building can sustain a PGA of 1.01g before losing its safety in the case of no pounding and a PGA of 0.93g in the case of 7-9 pounding. Also, the 7-storey building can sustain a PGA of 1.26g before collapse in the case of no pounding and a PGA of 1.18g in the case of 7-9 pounding. In this case, pounding is considered destructive to the colliding buildings as the 7-storey building is found to be capable to sustain higher PGAs before reaching certain performance level in the case of no pounding than in the case of pounding. Therefore, it can be concluded that pounding could be beneficial and destructive.

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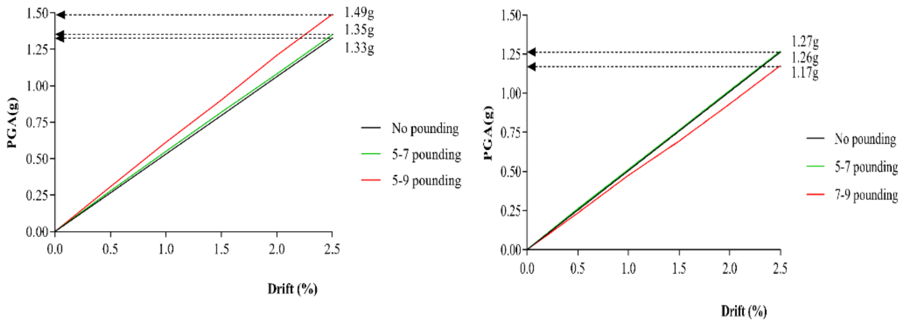
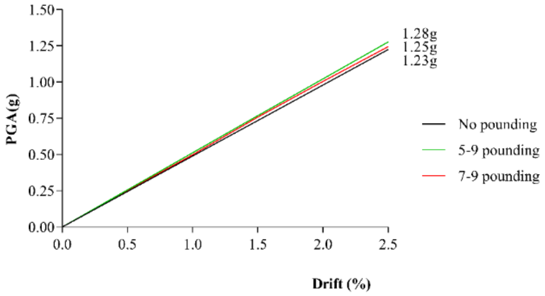


(a) 5-storey building (b) 7-storey building



(c) 9-storey building

Fig. 2. Average IDA curves of the considered buildings in different pounding scenarios

5. Fragility assessment

In this section, the fragility curves are presented. The fragility curves have been developed based on the IDA curves presented in section 4. Figure 3 presents the fragility curves for the 5-storey building in different pounding scenarios. The fragility curves for the 7-storey and 9-storey buildings in different pounding scenarios are not presented in this paper due to space limitations. Through comparing the response of the 5-storey building in different pounding scenarios with the no pounding case (Figure 3), it can be seen that a PGA of 0.35g, 0.7g and 1.05g leads to 99% damage at the OP, IO and DC performance levels respectively in both pounding scenarios (5-7 and 5-9 pounding scenarios). However, the same PGA leads to 90% damage of the 5-storey buildings in the no pounding case at the OP, IO and DC levels, respectively. It can be concluded here that pounding is destructive in this case as it leads to higher probability of damage. Moreover, through comparing the response of the 5-storey building in different pounding scenarios with the no pounding case (Figure 3), it can be seen that a PGA of 0.25g, 0.5g, 0.75g, 1.0g and 1.25g leads to 36% damage at the OP, IO, DC, LS and CP performance levels respectively in the no pounding case. However, the same

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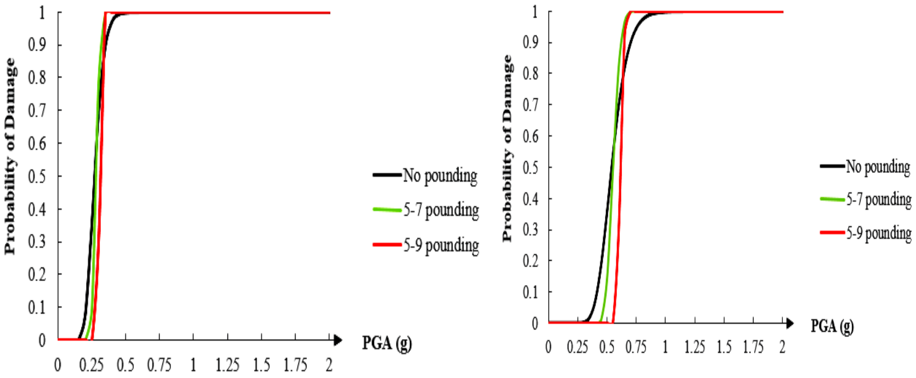
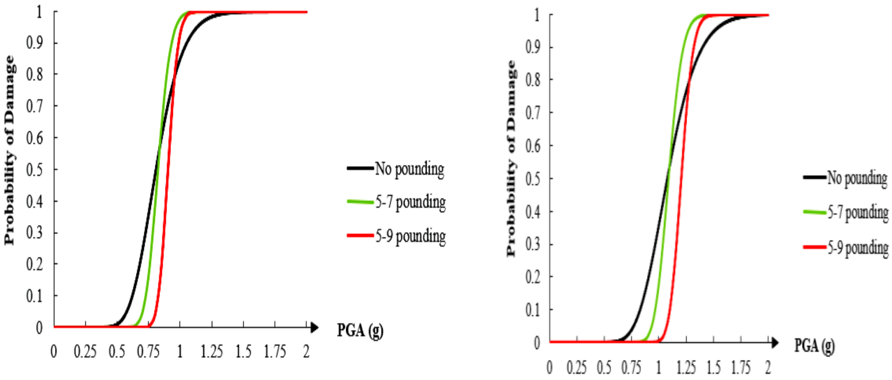


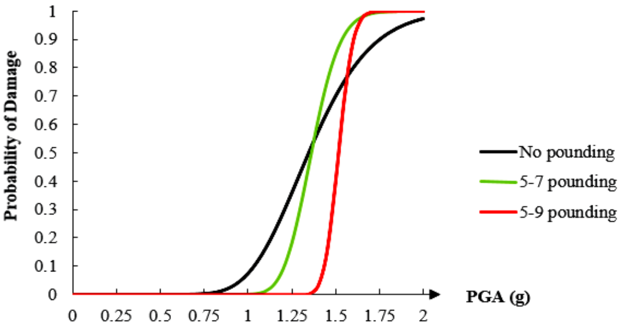
(a) OP

(b) IO



(c) DC

(d) LS



(e) CP

Fig. 3. Fragility curves of the 5-storey building in different pounding scenarios

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PGAs leads to 0% damage of the 5-storey buildings in the 5-9 pounding case and 10%, 15%, 17%, 18% and 18% at the OP, IO, DC, LS and CP performance levels in the 5-7 pounding scenario, respectively. It can be concluded here that pounding is beneficial in this case as it leads to lower probability of damage.

Therefore, it can be concluded that pounding could be beneficial or destructive. This is illustrated in different pounding scenarios in different performance levels (see Figure 3 for details). No clear relation has been observed because pounding is a highly complicated phenomenon. Also, it can be concluded that in the same pounding scenario, pounding could be both beneficial and destructive depending on the structural response and ground motion shift versus time. The findings of the fragility assessment are compatible with those of the IDA findings.

6. Conclusion

This paper studies the significance of pounding phenomena using the IDA and fragility assessment methods. Three 3-D buildings have been considered which are 5-storey, 7-storey and 9-storey structures. Three pounding scenarios have been taken into account, i.e. pounding between 5-storey and 7-storey buildings, pounding between 5-storey and 9-storey buildings and pounding between 7-storey and 9-storey buildings. The IDA and fragility assessment have been performed for these three buildings vibrating separately as well as in pounding condition. The results show that pounding can be beneficial and destructive depending on the structural response and ground motion shift versus time. No clear relation was observed because pounding is a highly complicated phenomenon.

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