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RESPONSE OF BASE-ISOLATED BUILDINGS SUBJECT TO NEAR-FAULT GROUND MOTION CONSIDERING SEISMIC POUNDING

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ABSTRACT
Near-fault ground motions containing long-period pulses are expected to impose large seismic demands on base-isolated buildings. A review of previous studies on the performance evaluation of base-isolated buildings under near-fault ground motions shows that these studies lack in the consideration of seismic pounding and the use of lower bound and upper bound values of isolator properties, according to the current state of practice. Therefore, in this study the performance of a typical four-story base-isolated reinforced concrete (RC) building is evaluated to investigate the influences of (i) pulse-like nature of near-fault ground motions and (ii) seismic pounding with retaining walls at the base. A set of 14 near-fault pulse-like ground motions scaled to represent the risk-targeted maximum considered earthquake (MCE_R) is used and nonlinear finite element analyses are carried out. It is found that the building response indicators are significantly increased due to seismic pounding. Nonetheless, if a bounding analysis is conducted, consideration of seismic pounding in the analysis does not have appreciable consequences on the prediction of damage to structural elements and drift-sensitive nonstructural components, while dramatic increase in floor accelerations due to pounding is critical for acceleration-sensitive nonstructural components.

Keywords: Base isolation, bounding analysis, near-fault ground motion, seismic pounding.

1. INTRODUCTION
Base isolation is widely considered as an efficient technique to improve seismic performance of buildings. Nonetheless, near-fault ground motions containing long-period pulses are expected to induce unacceptably large seismic demands on base-isolated buildings. The most desirable performance of base-isolated buildings where damage to structural and nonstructural components is reduced or even eliminated, is achieved when the superstructure remains essentially elastic and seismic pounding with retaining walls at the base does not occur. However, extreme nonlinear response of the superstructure and seismic pounding with retaining walls at the base are two potential consequences of strong near-fault ground motions acting on base-isolated buildings (Hall et al. 1995). Previous studies indicate that the near-fault ground motions have adverse effects on

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seismic performance of such buildings (Hall et al. 1995; Jangid and Kelly 2001; Providakis 2009; Mazza and Vulcano 2012). However, except the work of Hall et al. (1995), the other studies have been carried out without considering seismic pounding of buildings with adjacent structures. Hall et al. (1995) presented an example of a base-isolated building considering nonlinear behavior of the superstructure and seismic pounding with retaining walls at the base, using a two-dimensional numerical model, subject to N-S component of Sylmar ground motion from the Northridge earthquake. It is noted that there have been many previous studies that investigated seismic pounding of base-isolated buildings, but those studies were not focused on the important issue of near-fault ground motion (Masroor and Mosqueda 2012; Pant and Wijeyewickrema 2012). Furthermore, previous studies on near-fault ground motions or seismic pounding have not considered bounding values of isolator properties according to the current state of practice. Therefore, rigorous analysis of base-isolated buildings subject to a suite of near-fault ground motions is required.

In the present study the performance of a typical four-story base-isolated reinforced concrete (RC) building is evaluated using a three-dimensional nonlinear finite element (FE) model, considering bounding values of isolator properties, to investigate the influences of (i) pulse-like nature of near-fault ground motions and (ii) seismic pounding with retaining walls at the base. A set of 14 near-fault pulse-like ground motions scaled to represent the risk-targeted maximum considered earthquake (MCE$_R$), is used. Material and geometric nonlinearities are considered in the analyses.

2. BASE-ISOLATED BUILDING MODEL AND EARTHQUAKE GROUND MOTIONS

The base-isolated RC moment-frame building considered in this study is a four-story, three-bay by three-bay symmetric structure (Figure 1). The retaining walls around the building extend from ground level up to the base level. The building is 18 m x 18 m in plan, with a story height of 4.0 m, except for the first story which is 4.5 m high. The building was designed for a high seismicity region by the ELF procedure to meet the requirements of the 2012 International Building Code (ICC 2012). The designed isolation system for the building consists of lead rubber bearing (LRB) isolators. Bounding values of isolator properties were considered and the total maximum displacement of the isolation system using the lower bound properties of isolators $D_{tm} = 440$ mm.

A three-dimensional FE model of the building was developed in OpenSees (2012). Force-based, Euler-Bernoulli fiber beam-column elements that account for the spread of inelasticity along the length of the element were used to model beams and columns. For the concrete and the reinforcing steel, the constitutive models of Park et al. (1982) and Menegotto and Pinto (1973), respectively were used. Out-of-plane stiffness of the slabs was neglected, while in-plane stiffness was accounted for by using rigid truss elements connecting two ends of each beam and opposite corners of each slab of every bay. Elastomeric bearing elements available in OpenSees (2012) were used to model lead rubber bearings. In these elements a bilinear hysteretic model is used to represent the horizontal force-deformation relationship. Impact was modeled using zero length
elements, which were used as contact elements between the building and the retaining walls (Figure 1). The contact elements were based on the modified Kelvin-Voigt model (Pant and Wijeyewickrema 2012), where the total stiffness of the spring elements on either side of the base slab, computed as the axial stiffness of the slab is 5,000 MN/m and the coefficient of restitution is 0.65. Retaining walls were modeled as rigid objects and backfill soil-structure interaction was considered outside the scope of this study.

A set of 14 near-fault pulse-like ground motions was selected from the Pacific Earthquake Engineering Research (PEER) Center database (PEER 2011). The ground motions rotated to fault-normal (FN) direction were used. The pulse-like nature of a ground motion was identified using the method developed by Baker (2007). The selection of the motions was made in such a way that the mean 5%-damped acceleration response spectrum for the ground motions closely follows the MCE\(R\) spectrum in the selected period range of \(0.5T_D - 1.25T_M\), where \(T_D\) and \(T_M\) are the effective periods at the design earthquake (DE) and the MCE\(R\), respectively.

![Figure 1: The four-story building considered in the present study.](image)

**Figure 1:** The four-story building considered in the present study.

### 3. NONLINEAR TIME-HISTORY ANALYSIS RESULTS

Nonlinear time-history analyses were carried out, first by assuming that a sufficient separation distance is available between the building and the retaining walls such that pounding does not occur, and then by setting the separation distance equal to the total maximum displacement of the isolation system, to investigate the effects of seismic pounding. The ground motions were used for unidirectional excitation as shown in Figure 1. Here the numerical models of the base-isolated building with lower bound and upper bound properties of isolators are referred to as lower bound (LB) model and upper bound (UB) model, respectively.

Figure 2 presents peak relative base displacements, under individual ground motions, without considering pounding. Also shown in Figure 2 is a dashed line denoting \(D_{TM} = 440\) mm, and mean values of the peak displacements. The value of the base displacement under any ground motion exceeding \(D_{TM}\) indicates the potential for pounding assuming that the separation distance is equal to \(D_{TM}\). It is observed that several of the ground motions have the potential for pounding. Furthermore, while peak values under several ground motions exceed \(D_{TM}\), the mean
values, which were found to be 383 mm using the lower bound model and 296 mm using the upper bound model, are much smaller than $D_{TM}$. Figure 2 clearly highlights the importance of considering seismic pounding in the analysis of base-isolated buildings subject to near-fault pulse-like ground motions.

![Figure 2: Peak relative base displacements without considering pounding.](image)

For superstructure, the peak response indicators are presented as the mean as well as 84\(^{th}\) percentile (i.e., mean plus one standard deviation) values from the time-history analysis. While response of the building is mainly evaluated in terms of the mean values, 84\(^{th}\) percentile values are used to discuss the dispersion of the response indicators under individual ground motions from the mean. In this study, peak inter-story drift ratios in the ranges of 0.2–0.5\%, 0.5–1.5\%, and 1.5–3\% correspond to damage of drift-sensitive nonstructural components, moderate structural damage, and severe structural damage, respectively (Elnashai and Di Sarno 2008). When pounding was not considered in the analysis, the superstructure response of the building is governed by the upper bound model (Figure 3). Therefore, performance of the building herein is discussed in reference to the upper bound model, unless noted otherwise. Mean of the peak inter-story drift ratios reaches a maximum value of 0.74\% at the first story and remains less than 0.5\% at the upper stories, indicating some moderate damage only at the first story (Figure 3(a)). This might be acceptable for the building under consideration because $R = 2$ was used in the design. However, this might not be acceptable for the critical facilities such as hospitals and emergency management centers where, $R = 1$ is more common in design practice. The mean values of the peak floor accelerations at all the floor levels remain within the acceptable limit of 0.35\(g\), indicating that the pulse-like characteristics of earthquakes are more important from the view point of damage to structural elements and drift-sensitive nonstructural components rather than the damage to acceleration-sensitive nonstructural components (Figure 3(b)). Furthermore, larger dispersions in the response indicators are observed using upper bound model than those using the lower bound model (Figure 3).

When pounding was considered in the analysis (Figure 4), it is observed that in contrast to the no-pounding case (Figure 3), the superstructure response of the building is governed by the lower bound model instead of the upper bound model. Therefore, performance of the building herein is discussed in reference to the lower bound model, unless noted otherwise. Here mean of the peak
inter-story drift ratios reaches a maximum value of 0.98% at the first story, reaches 0.54% at the second story, and remains less than 0.5% at the upper stories, indicating moderate damage only at the bottom two stories (Figure 4(a)). Mean of the peak floor accelerations reaches a maximum value of $3.7\,g$ at the base level, and exceeds a value of $0.35\,g$ at all the floor levels (Figure 4(b)). Comparison of the Figures 3 and 4 reveals that the effects of seismic pounding are highly pronounced in the immediate vicinity of impact i.e., at the first story. In addition, the difference between the $84^{th}$ percentile and mean values indicates that the dispersion of the response indicators is increased significantly due to pounding. Furthermore, when pounding is considered, larger dispersions are observed using upper bound model, compared with the lower bound model, similar to the no-pounding case. It is observed that if analysis of base-isolated buildings is conducted according to the current state of practice of (i) employing 7 or more ground motions and using mean values of response indicators and (ii) conducting bounding analysis and investigating the maximum effects of the lower bound and upper bound models, the mean values of peak inter-story drift ratios and floor accelerations at the first story considering pounding are 1.3 and 11.2 times, respectively larger than the no-pounding case (Figures 3 and 4).

**Figure 3**: Mean and $84^{th}$ percentile values of peak superstructure response indicators *without considering pounding*.

**Figure 4**: Mean and $84^{th}$ percentile values of peak superstructure response indicators *considering pounding*. 
4. CONCLUDING REMARKS

Near-fault pulse-like ground motions can impose very large displacement demands on base-isolated buildings and can have the potential to induce seismic pounding with adjacent retaining walls. It was found for the building and the ground motions considered in this study that the building response indicators are significantly increased due to seismic pounding, but if a bounding analysis is conducted, consideration of seismic pounding in the analysis does not have appreciable consequences on the prediction of damage to structural elements and drift-sensitive nonstructural components. However, dramatic increase in floor accelerations due to pounding is critical for acceleration-sensitive nonstructural components. The adverse effects of pounding are mostly concentrated in the immediate vicinity of impact i.e., at the first story. Analysis results reveal that the response indicators in the instances of pounding are characterized by significantly larger dispersions from the mean values, compared with the no-pounding cases.

REFERENCES


