INVESTIGATING THE P-DELTA EFFECTS ON THE SEISMIC COLLAPSE CAPACITY OF ADJACENT STRUCTURES

Benyamin MOHEBI1, Farzin KAZEMI2, Mansoor YAKHCHALIAN3

ABSTRACT

Pounding between structures during earthquakes has been a subject of research for many years, and researchers have considered a variety of conditions of adjacent structures in their studies. The pounding phenomenon includes some factors such as cracking, plastic deformation, energy dissipation, friction and fracture due to impact. The purpose of this study is to evaluate the P-delta effects on the seismic collapse capacities of pounding structures assuming different values of clear distance among them. For this purpose, 2-, 4- and 6-story structures with different values of clear distance, having linear viscoelastic contact elements in floor levels among them, are assumed. Nonlinear Multi-Degree-of-Freedom (MDOF) stick models are applied to simulate Moderately Ductile (MD) structures representing steel intermediate moment-resisting frames. It is worth mentioning that an algorithm is used to remove the collapsed structure during the Incremental Dynamic Analyses (IDAs) to compute the seismic collapse capacities of both structures using the OpenSees software. Furthermore, in contrast to many studies that investigated pounding without considering the P-delta effect, two types of models with and without considering the P-delta effects are analyzed. The results indicate that considering the P-delta effect in modeling has a significant influence on the seismic collapse capacities of the structures and the impact forces. Also, the results indicate that the existence of the P-delta effect and insufficient clear distance between the structures affect the acceleration and other responses of the structures.

Keywords: P-delta effects; Structural pounding; Seismic collapse capacity; Incremental dynamic analysis; Impact force.

1. INTRODUCTION

In flexible structures, gravity loads acting through lateral displacements magnify structural deformations, which is usually termed as P-delta effect. The P-delta effect becomes significant at large inelastic deformations because it leads to a negative slope in the post-yield range of the lateral load-displacement relationship. The P-delta effect occurs in every structure that is subject to axial load. The magnitude of the P-delta effect is related to the slenderness of elements, and the magnitude of the axial load, P. There are two types of P-delta effects, large P-delta (P-Δ) and small P-delta (P-δ). Large P-delta occurs when the vertical loads acting on the laterally displaced structure and small P-delta refers to the axial load in an individual element subjected to the deflection between its end nodes. The P-delta effect contributes to the deformations of the structure so that it causes higher deformations, which induce additional moments and stresses in structural members. Many researchers studied the P-delta effect in structures, experimentally, analytically and numerically. Kanvinde (2003) and Vian and Bruneau (2003) conducted experimental studies on the P-delta effect on single-degree-of-freedom (SDOF) structures. In comprehensive parameter studies, Miranda and Akkar (2003) presented an equation to evaluate the minimum lateral strength of P-delta induced collapse on SDOF structures.

1Assistant Professor, Department of Civil Engineering, Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran, mohebi@eng.ikiu.ac.ir
2MSc in Earthquake Engineering, Department of Civil Engineering, Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran, farzin.kazemi@edu.ikiu.ac.ir
3Assistant Professor, Department of Civil Engineering, Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran, yakhchalian@eng.ikiu.ac.ir
Black (2011) presented two stability coefficients, quantifying the P-delta effect in moment-resisting frames. He derived closed-form expressions from analytical considerations for the so-called modal-elastic stability coefficient and through regression analyses for the modal-inelastic stability coefficient. In general, the P-delta effect is initially governed by the fundamental mode shape. However, the P-delta effect is affected by the change of the deflected shape, and it is amplified in the stories in which the inter-story drift becomes large (Aydinoglu 2001; Jennings and Husid 1968). Adam and Jager (2012) introduced a collapse assessment methodology by means of the so-called collapse capacity spectra to assess the P-delta effect on the seismic collapse capacity of SDOF structures. Gharyanpoor et al. (2017) evaluated the collapse capacity of SDOF structures with taking the P-delta effect and strength degradation into account in modeling. They concluded that the P-delta effect controls the collapse capacity of long period structures with and without supplemental viscous damping. To reduce the collapse capacity dispersion of SDOF systems vulnerable to the P-delta effect, Tsantaki et al. (2017) proposed a seismic intensity measure (IM), which is the geometric mean of pseudo-spectral accelerations over a range of periods. Adam et al. (2017) modified this IM for generic moment frames to account for the higher mode effects. They showed that the modified IM provides minimum dispersion for the entire set of purely P-delta vulnerable frames with a different number of stories. Yakhchalian et al. (2014a) and (2017) proposed new proxies for ground motion selection for seismic collapse assessment of long- and short-period structures, respectively.

During earthquakes, adjacent structures with an insufficient separation distance between them may experience earthquake-induced structural pounding. This phenomenon can cause local damage, substantial damage at the contact locations or even total collapse of structures. Many researchers confirmed that the reason for pounding between adjacent structures is the difference between their fundamental periods, which comes from difference in mass or stiffness (Anagnostopoulos 1988; Anagnostopoulou and Spiliopoulos 1992; Maison and Kasai 1992; Karayannis and Favvata 2005; Jankowski 2007; Komodromos 2008; Mahmoud and Jankowski 2009; Polycarpou and Komodromos 2010a). Several studies were carried out to minimize structural damages during pounding by evaluating the appropriate separation distance between structures (Mahmoud et al. 2013, Soltyssik and Jankowski 2013, Abdel Raheem 2014). However, in large crowded cities, providing a large separation distance between structures is not an easy solution due to high land prices. Madani et al. (2015) considered different cases of adjacency for evaluating the effects of pounding and structure-soil-structure interaction (SSSI) on the behavior of adjacent structures. However, they did not consider the collapse probability in their work and neglected the P-delta effect in modeling.

The best approach to simulate structural pounding under earthquakes is to consider the actual condition of structure in modeling. According to the results of the previously mentioned studies, when the P-Delta effect is included in modeling, the results are substantially different. In other words, the P-delta effect plays a key role in the analysis of the structure, and it is well recognized that there is a need to apply sufficiently accurate methods to predict the P-delta effect on the seismic collapse capacity of multi-degree-of-freedom (MDOF) structures under seismic excitations. The purpose of this study is to evaluate the P-delta effect on the seismic collapse capacity, the impact forces, accelerations and other responses of adjacent pounding structures. For this purpose, 2-, 4-, and 6-story structures assuming different values of clear distance among them are considered. To analyze the structures, nonlinear MDOF stick models are applied, and for simulating the pounding between the structures, a linear viscoelastic contact element is used. According to the results of this study, the impact forces due to pounding between adjacent structures significantly increase when the P-delta effect is considered in modeling, and taking this effect into account leads to lower and more realistic seismic collapse capacity predictions.

2. PROCEDURES FOR MODELING OF POUNDING

Analyses were performed using two-dimensional MDOF stick models with numbers of stories, \( N \), equal to 2, 4, and 6, fundamental periods, \( T_1 \), of 0.2\( N \), and the height of all stories, \( h \), equal to 3.6 m. According to ASCE/SEI 7-10 (ASCE 2010), all the structures were assumed to be located at a site with high seismicity and soil class D. For the design of the structures, seismic risk category II (i.e., importance factor \( I=1.0 \)), and the seismic design parameters of \( S_{D05}=1.25g \) and \( S_{D01}=0.6g \) were considered. Figure 1 illustrates the typical floor plan of the structures. The gravity dead and live loads...
of 5.5 kN/m² and 2 kN/m² were applied to all stories, respectively. Response modification factors of \( R=4.5 \), for steel intermediate moment-resisting frames, were selected in accordance with ASCE/SEI 7-10 (ASCE, 2010). Therefore, 2Story-Inter, 4Story-Inter, and 6Story-Inter stick models representing intermediate steel moment-resisting frames, which have moderately ductile (MD) members were designed. To consider the P-delta effect in the analyses, gravity loads of \( D+0.25L \) were applied to all the structures according to ASCE/SEI 7-10 (ASCE 2010), where \( D \) is the dead load and \( L \) is the live load.

![Figure 2. Typical floor plan of the structures](image)

### 2.1 Nonlinear modeling of the structural members

Each stick model consists of elastic beam-column elements and zero-length elements representing the nonlinear behavior of the structure, which is based on the concentrated plasticity approach that plastification only occurs at the ends of the column of each story. The bilinear Ibarra-Medina-Krawinkler model (Ibarra et al. 2005) was applied in zero-length elements. Figure 2 indicates the typical backbone curve of each story with and without considering the P-delta effect, where \( K_e \) is the elastic stiffness of story, \( K_s = \alpha_s K_e \) is the strain-hardening stiffness of story, and \( K_c = \alpha_c K_e \) is the post-capping stiffness of story. Characteristic displacements of this relationship remain unchanged, whereas the characteristic forces are reduced. For modeling all rotational springs, the strain hardening coefficient, \( \alpha_s \), and post-capping coefficient, \( \alpha_c \), were selected as 0.03 and -0.1, respectively; and residual strength was neglected. In addition, for moderately ductile structures, \( \mu = \frac{\delta_c}{\delta_y} \) was assumed to equal 4.0.

![Figure 2. Typical backbone curve, with and without destabilizing P-delta effect](image)

### 2.2 Linear viscoelastic model

Some of existing contact elements, which do not have any damping mechanism, are not able to include
the energy dissipation during impact. As a result, using these contact elements to simulate the structural pounding may result in excessive unrealistic responses. The linear viscoelastic model is only active in compression, meaning that no energy dissipation is taken into account for when the pounding structures are distancing from each other. This model has been successfully used to simulate the pounding phenomenon with an acceptable accuracy. The linear viscoelastic model called Kelvin-Voigt model, which consists of a linear spring and a viscous damper, is able to consider the energy dissipation in pounding phenomenon (Jankowski et al. 1998; Polycarpou and Komodromos 2010b).

When using the linear viscoelastic model, the pounding force is expressed as:

\[
F(t)=K\delta(t)+C\dot{\delta}(t)
\]

(1)

where \(K\), \(C\), \(\delta\) and \(\dot{\delta}\) denote the impact stiffness coefficient between pounding structures with masses \(m_1\) and \(m_2\), the impact damping coefficient, relative deformation and relative velocity, respectively. The impact damping coefficient can be calculated as (Anagnostopoulos 1998):

\[
C=2\xi \sqrt{\frac{m_1 m_2}{m_1+m_2}}
\]

(2)

where \(\xi\) is the damping ratio related to the coefficient of restitution, \(e\), which is defined as the ratio of final relative velocity to the initial relative velocity of the impacting bodies. It takes values of 0.0, representing fully elastic, and 1.0, representing fully plastic impacts (Jankowski 2010). The damping ratio is calculated by the following relationship (Anagnostopoulos 2004):

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

(3)

Although several studies have been performed on the impact stiffness of pounding models, the impact stiffness depends on the colliding materials and there is no unique relation for its computation. Muthukumar and Desroches (2004) suggested approaches to calculate the impact stiffness of two pounding floors as the sum of their axial stiffness values. Polycarpou et al. (2014) considered a simple approximation to determine values for the stiffness coefficient required for pounding models. Stiffness value depends on the plan geometry and the material characteristics at the location of impact. The normalized impact stiffness, \(K_{\text{imp}}\), which is related to the moduli of elasticity of the pounding elements, can be approximated as follows:

\[
K_{\text{imp}} = \left[ \frac{1-v^2_1}{E_{\text{Dyn},1}} + \frac{1-v^2_2}{E_{\text{Dyn},2}} \right]^{-1}
\]

(4)

\[
E_{\text{Dyn},i}=5.82(E_{\text{St},i})^{0.63}, \text{ in GPa}
\]

(5)

where \(E_{\text{Dyn},i}\) is the dynamic elastic modulus of concrete, calculated based on experiment in terms of the static elastic modulus, \(E_{\text{St}}\), and the Poisson's ratio, \(\nu\) (Salman and Al-Amawee 2006). Assuming \(E_{\text{St}}=21\text{ GPa}\) and \(\nu=0.2\), the normalized impact stiffness was found to be \(K_{\text{imp}}=20.63\times10^6\text{ kN/m}^2\), which is based on the assumption that the materials of elements maintain elastic during the pounding. Then, the impact stiffness coefficient, \(K\), was determined to be \(4.126\times10^8\text{ kN/m}\) by multiplying \(K_{\text{imp}}\) by the length of the plan corresponding to the pounding side, \(L=20\text{ m}\). The coefficient of restitution, \(e\), was considered equal to 0.65 for concrete-to-concrete impact, and hence the impact damping coefficient, \(C=5791.23\text{ kN/s/m}\), was calculated using Equation 2.

2.3 Structural models

To prevent the pounding phenomenon, adjacent structures should be separated at an acquired minimum separation distance, \(d\). According to ASCE/SEI 7-10 (ASCE 2010), adjacent structures
should be separated at least $\delta_{MT}$, determined as follows:

$$\delta_{MT} = \sqrt{\left(\frac{C_d \delta_{max}}{I}\right)^2 + \left(\frac{\delta_{max}}{I}\right)^2}$$  \hspace{1cm} (7)$$

where $\delta_{MT}$ is the maximum inelastic displacement, $\delta_{max}$ is the maximum elastic displacement, $C_d$ is the deflection amplification factor, and $I$ is the importance factor.

In this study, a parametric investigation was performed to evaluate the P-delta effects on seismic collapse capacity of pounding structures. For this purpose, four values of clear distance equal to 0.0, 0.5$d$, 1.0$d$ and 1.5$d$ were considered, where $d$ is equal to $\delta_{MT}$ prescribed by Equation 7. Table 1 presents all the cases of adjacent structures assumed, having different heights and clear distances. In order to compare the results, the 2Story-Inter, 4Story-Inter and 6Story-Inter models were also analyzed without any adjacent structure. Moreover, all the analyses were repeated assuming the story mass for all the stories in one of the adjacent structures equal to 1.5 times that previously assumed, to consider the effects of difference between the mass of pounding floors. For instance, the story mass for the 4Story-Inter-1.5M structure is 1.5 times that assumed for the 4Story-Inter structure.

<table>
<thead>
<tr>
<th>Adjacent Structures</th>
<th>C.D=0.0 (m)</th>
<th>C.D=0.5 (m)</th>
<th>C.D=1.0 (m)</th>
<th>C.D=1.5 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2Story-Inter and 4Story-Inter</td>
<td>0.0</td>
<td>0.052</td>
<td>0.104</td>
<td>0.156</td>
</tr>
<tr>
<td>2Story-Inter and 6Story-Inter</td>
<td>0.0</td>
<td>0.056</td>
<td>0.112</td>
<td>0.168</td>
</tr>
<tr>
<td>4Story-Inter and 6Story-Inter</td>
<td>0.0</td>
<td>0.127</td>
<td>0.255</td>
<td>0.382</td>
</tr>
<tr>
<td>2Story-Inter and 4Story-Inter-1.5M</td>
<td>0.0</td>
<td>0.052</td>
<td>0.104</td>
<td>0.156</td>
</tr>
<tr>
<td>2Story-Inter and 6Story-Inter-1.5M</td>
<td>0.0</td>
<td>0.056</td>
<td>0.112</td>
<td>0.168</td>
</tr>
<tr>
<td>4Story-Inter and 6Story-Inter-1.5M</td>
<td>0.0</td>
<td>0.127</td>
<td>0.255</td>
<td>0.382</td>
</tr>
</tbody>
</table>

3. THE NUMERICAL ANALYSIS AND RESULTS

Incremental Dynamic Analyses (IDAs) were performed using 48 near-field ground motion records selected by Yakhchalian et al. (2014b) for seismic collapse assessment of structures. The most common scalar intensity measure, $S_a(T_1)$, was selected as the IM for performing IDAs. All of the ground motions were scaled to the different intensity levels until the collapse occurs. To capture the seismic collapse capacity of the structures efficiently, the Hunt and Fill algorithm was applied (Vamvatsikos and Cornell 2002). In a contact element, the impact stiffness coefficient, $K$, is larger than the story stiffness, so the required time step should be small to accurately estimate the impact forces (Anagnostopoulos 1988). Thus, an algorithm was developed to consider a maximum time step of 0.0005 sec, when the pounding is probable. Furthermore, the developed algorithm provides the ability for the automated removal of the collapsed structure during the analysis. The procedure used in this study was implemented by using MATLAB (MATLAB 2014) and OpenSees (McKenna et al. 2016) softwares.

3.1 Lateral response of stories

Figures 3 and 4 show the structural responses obtained for the 4Story-Inter and 6Story-Inter pounding structures. According to these figures, large differences are observed between the peak values of the inter-story drifts, velocities, and accelerations. Figure 3 shows that during pounding, inter-story drifts, velocities, and accelerations of the 4Story-Inter structure at the upper floors reach the peak values.
However, as shown in Figure 4, the peak values for the 6Story-Inter structure are reached in lower floors especially in the impacting floors. It can be seen that pounding changes the structural characteristics of the pounding structures. Therefore, during pounding, the structures indicate characteristics different from those observed without considering pounding.

Figure 3. Peak responses of the 4Story-Inter structure during pounding

Figure 4. Peak responses of the 6Story-Inter structure during pounding
3.2 Story acceleration

Figure 5 presents the acceleration time-histories at the top floors of the 4Story-Inter and 6Story-Inter pounding structures under a record of the Northridge earthquake (Pacoima Dam, CDMG station 24207), given $S_a(T_1) = 3g$. By comparing the time-histories of the case without clear distance and the case with a clear distance equal to $d$, high values of the acceleration response are observed at the time of impact. Considering the computed peak floor accelerations of the structures, the influence of pounding in response is much more pronounced at the zero separation distance. The results obtained from this figure indicate that the acceleration response is affected by separation distance, in which these differences in acceleration values can change the amount of damage in structural elements. Thus, when the separation distance increases to $d$, the number of pounding occurrences decreases correspondingly. The reason for discontinuing the acceleration time-histories of the 6Story-Inter structure between 5 and 6 sec, given clear distances of 0.0 and $d$, is the collapse of this structure.

![Acceleration time-histories](image)

Figure 5. Acceleration time-histories at the top floor of the 4Story-Inter and 6Story-Inter pounding structures for values of clear distance equal to 0.0 and 1.0$d$

3.3 Impact Force

The impact force time-histories for the 4Story-Inter and 6Story-Inter pounding structures subjected to a record of the Northridge earthquake (Pacoima Dam, CDMG station 24207), given $S_a(T_1) = 3g$, are presented in Figure 6. The results obtained in this figure indicate that when the P-Delta effect was neglected, the maximum impact force decreases correspondingly. Therefore, considering the P-Delta effect, influences the impact force values significantly. Thus, taking the P-Delta effect into account has more influence on the median collapse capacity of the taller structure. The graphical results of impact forces for pounding between the 4Story-Inter and 6Story-Inter structures are presented for the Northridge ground motion. Similar results were obtained from the other considered ground motion records.
Figure 6. Impact force time-histories at the first floor of the 4Story-Inter and 6Story-Inter pounding structures

3.4 IDA curves

Figure 7 illustrates the IDA curves for the 2Story-Inter and 6Story-Inter pounding structures, given the clear distance equal to 1.0d. In these figures, each of the 48 IDA curves is displayed and the bold black line shows the median of IDA curves. The median collapse capacities of the 2Story-Inter structure for separation distances of 1.0d is equal to 2.66 g, whereas the corresponding median collapse capacities of the 6Story-Inter structure is 0.51 g.

Figure 7. IDA curves for the 2Story-Inter and 6Story-Inter pounding structures with separation distance equal to 1.0d

For better investigating the results of IDA analyses, the median collapse capacity of each of the pounding structures was divided by the median collapse capacity of that structure without any adjacent structure. Afterwards, the effect of P-delta on the normalized collapse capacity of the adjacent pounding structures is evaluated. Figure 7 compares the normalized collapse capacities of the 2Story-Inter and 4Story-Inter pounding structures computed with and without considering the P-delta effect. It can be seen that when taking the P-delta effect into account, the normalized collapse capacity of the 4Story-Inter structure decreases by an average of 28%. Figure 8 compares the normalized collapse capacities of the 2Story-Inter and 6Story-Inter pounding structures. In this figure, the P-delta effect decreases the normalized collapse capacity of the 6Story-Inter structure by an average of 25%. Figure 9 indicates the results of evaluating the effects of story mass increase in the adjacent structures on the normalized collapse capacity of the pounding structures with and without considering the P-delta effect. According to the results presented in this figure, as the story mass of the adjacent taller structure increases from M to 1.5M, the P-delta effect decreases the normalized collapse capacity of the 4Story-Inter-1.5M structure by an average of 27%.
Figure 7. P-delta effect on the normalized collapse capacity of the 2Story-Inter and 4Story-Inter pounding structures with equal story mass M

Figure 8. P-delta effect on the normalized collapse capacity of the 2Story-Inter and 6Story-Inter pounding structures with equal story mass M

Figure 9. P-delta effect on the normalized collapse capacity of the 2Story-Inter and 4Story-Inter pounding structures with story mass M and 1.5M

Figure 10. P-delta effect on the normalized collapse capacity of the 2Story-Inter and 6Story-Inter pounding structures with story mass M and 1.5M

Also, in Figure 10, which shows the normalized collapse capacity of the 2Story-Inter-1.5M and 6Story-Inter-1.5M pounding structures, the P-delta effect decreases the normalized collapse capacity
of the taller structure. Thus, it can be inferred that the P-delta effect has more influence on the median collapse capacity of the taller structure. It should be mentioned that the results observed, are valid for all the pounding cases presented in Table 1.

4. CONCLUSIONS

In this research, a comprehensive study was performed to assess the P-delta effect on the seismic collapse capacities of pounding structures. For this aim, different cases of adjacent structures and the four aforementioned clear distances were considered. The results obtained are summarized as below:

- According to the results, large differences are observed between the peak values of the inter-story drifts, velocities, and accelerations of the pounding structures. Furthermore, it can be seen that during pounding, the structural responses in the lower floors of taller structure reach their peak values in contrast with the cases of neglecting pounding.
- The results of comparing response time-histories show that at the time of pounding between structures, high values of acceleration response are observed in the case with zero separation distance, which is highly affected by impact.
- The results obtained from the impact forces illustrate that by neglecting the P-Delta effect, the maximum impact force decreases. Hence, considering the P-Delta effect to simulate the behavior of pounding structures, increases the values of impact forces significantly.
- It was demonstrated that the normalized collapse capacities of the pounding structures computed without considering the P-delta effect, are greater than those considering the P-delta effect. Moreover, the P-delta effect has more influence on the median collapse capacity of the taller pounding structures.

5. REFERENCES


American Society of Civil Engineers. (2010). Minimum design loads for buildings and other structures (Vol. 7). Amer Society of Civil Engineers.


