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Ahmad Baset Popal, Zabihullah Dalil Shinwari, Iqbal Irshad, Abdul Sattar Nawabi and Sayed Javid

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Article

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Ahmad Baset Popal
Zabihullah Dalil Shinwari
Iqbal Irshad
Abdul Sattar Nawabi
Sayed Javid

Abstract

Population increment encourages engineers to build high-rise structures. However, in high-rise structures lateral load has a more severe impact on the structure than axial loads and this effect is known as the P-Delta effects. The current study aims to evaluate P-Delta effects in a high-rise structure located in Kabul city and to pinpoint the minimum height required for considering P-Delta effects in structural analysis. The analysis is carried out utilizing the response spectrum method performed by ETABS software for a total of five models with a different number of storey and lateral load-resisting systems. It is observed that with the increase in lateral stiffness, P-Delta effects can be minimized to a certain extent. Lateral displacement, storey drift and stability coefficient are some of the other parameters considered for comparison purposes which are significantly mitigated while a shear wall is provided. Also, an adequate and proper positioning of shear walls has resulted in an appropriate solution for minimizing the P-Delta effects.

Keywords: *P-Delta effect, Lateral displacement, Lateral stiffness, Stability coefficient.*

Introduction

Structures are usually subjected to two types of loads namely lateral and gravity loads. Analysis and design of structures are performed in such a way that they can safely withstand these loads. Gravity loads are transferred throughout the frame from slabs to beams to columns to the foundation and finally to natural ground, while lateral loads are resisted by the diaphragm and lateral load resisting systems. These systems can be used both, in low- and high-rise buildings [1].

Lateral displacement, overturning moment, base shear, beam shear, column shear and storey drift are some of the structural response parameters mostly affected by lateral loads [1]. In the traditional first order analysis of structures, the effects of change in the structure actions due to structure deformations are neglected. However, when a structure deforms, the applied loads may cause additional actions in the structure that are called second order or P-Delta effects [2]. Lateral loads may cause second-order effects or geometric-nonlinearity effects on buildings which might cause failure particularly, in high-rise buildings. Low-rise buildings are mostly analyzed using linear static analysis which is not appropriate for high-rise buildings. This is because some of its assumptions are not applicable in multi-storey buildings [3].

As the population increases and land use gets limited, high-rise buildings are designed to fulfil human needs. When building height increases, at a certain stage second-order effect becomes significant. Second-order effects refer to the fact that as the structure deflects under loads, deformations can cause initial loads to induce further stresses on the building that are not considered in the first-order analysis. The second order or P-delta effect is the additional action induced by the axial load when there is a horizontal displacement on a vertical element. It is worth mentioning that other phenomenon such as applied axial load, lateral and torsional stiffness of building, the level of its eccentricity, mass moment of inertia, height, the properties of loading and ground motions have a direct relation with the severity of P-delta effects [4].

1.1 Problem Statement

As buildings get higher, P-delta effects also increase especially, in eccentric and slender buildings. In high-rise buildings, P-Delta effects are the main cause of failure. Prevention of this phenomenon is a considerable problem to tackle. Consideration of P-Delta analysis enables the structure to withstand these additional loads, but since P-Delta consideration is not necessary for all structures, it is the main focus to determine at which height should this phenomenon be considered. While an increment in lateral stiffness is suggested as the ideal solution to minimizing the P-Delta effect, it is essential to increase lateral stiffness to a rational amount, considering that if lateral stiffness is too large then overturning moment might be the main cause of structural failure.

1.2 Study Objectives

- To evaluate P-Delta effects in high-rise buildings.
- To compare the P-Delta effects between moment resisting frame and frame with shear walls.
- To investigate optimum solutions for minimizing P-delta effects in high-rise buildings.

1.3 Significance of Study

The P-Delta effect is a sensitive topic to consider while designing especially, for high-rise buildings. Because this phenomenon may cause over-stress in members and can be the main cause of the structure's failure.

2. Review of Literature

Several studies have been performed on the P-Delta effect in reinforced concrete structures. Many researchers have investigated the P-Delta effect while considering different factors such as lateral displacement, overturning moment, eccentricity, storey drift and lateral load-resisting system.

2.1 P-Delta Effect

The P-Delta effect is a non-linear second-order effect which exhibits a considerable increase in the base moment when a structure is subjected to a large lateral displacement due to seismic or wind load. The P-Delta effect lies under the geometric non-linearity which is a term for non-linearity due to excessive deformation or deflection of material in a structure, even if they are in the elastic limit. When a structure is loaded it will deflect due to the stress applied to it. This deflection is said to be the first-order effect. Without any additional loading, if any stress or adverse effects are induced in a structure due to the first-order deflection, it is called the second-order effect. Usually, while analyzing, structures are considered in a static position and loads are applied to them. P-Delta analysis uses the same philosophy but while considering the structure as a deformed shape due to the first order effect [5].

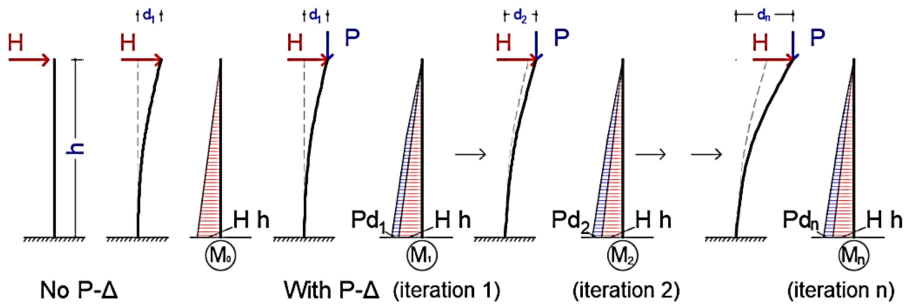

Figure 1: P-Delta Effect [5]

If we consider a member like a column with a height of (h) and a lateral load of (H) with an axial load of (P) acting on it. It is observed that as load (H) acts on the column, the base moment is $(H \cdot h\ )$ and a lateral displacement of (d_1) is visible. This is where things get interesting as it is visible the lateral displacement d_1 causes an additional moment of (P$\times$$d_1$) which indicates that the total base moment is $(H \cdot h\ +\ P \cdot d_1)$. But wouldn't this moment cause additional lateral displacement (d_2)? and now the base moment will be $(H \cdot h\ +\ P \cdot d_2)$. This goes up to several iterations until the increase in deflection is a negligible number and does not affect the base moment significantly. But as lateral load acts on a structure or maybe a member, the lateral load causes lateral displacement on the member (Δ) and the axial load acting on the member shifts from the original position and causes an additional moment due to lateral displacement (Δ) and axial load (P). Hence, the term P-Delta is used [5].

Or if we discuss figure.2, a column with a length of (L) affected by a lateral load of (V) and an axial load of (P) is considered.

In standard linear static analysis, we can find lateral deflection (Δ) as:

$$\Delta = \frac{M\,L^2}{3EI} = \frac{V\,L^3}{3EI} \quad [5]$$

$$M\ =\ V\ \times\ L \quad [6]$$

It is noted that in the case of linear static analysis, deflection has a direct relation with the lateral load. But if the column is affected by an axial load (P), the column would deflect more and the relation will change as;

$$\sum M =\ M_1 + M_2 \quad [6]$$

Where,

$$M_1 = (V \times L) \quad [6]$$

$$M_2 = (P \times \Delta) \quad [6]$$

$$\Delta_{\,1} = \frac{M_1\,L^2}{3EI} = \frac{V\,L^3}{3EI} \quad [6]$$

$$\Delta_{\,2} = \frac{M_2\,L^2}{2EI} = \frac{P\Delta\,L^2}{2EI} \quad [6]$$

Where Δ_{Total} due to lateral and axial loads is equal to,

$$\Delta_{Total} = \frac{V\,L^3}{3EI} + \frac{P\Delta\,L^2}{2EI} \quad [6]$$

In the last relation for total lateral displacement, it is observed that lateral displacement is directly affected by the member's length, lateral load and axial load. It indicates that with an increase in any of the named factors, lateral displacement increases especially, length having a parabolic relation with displacement.

Increment in elastic modulus and moment of inertia are of the main parameters which can be used to minimize lateral displacement and in larger scope P-Delta effect.

The geometry of member is also a valid point for consideration since the moment of inertia is,

$$I = \frac{b \times h^3}{12} \quad [6]$$

As observed in the formula, inertia can be significantly increased by adding to member height, so this phenomenon is also worth considering [6].

2.2 Lateral Displacement

Analyzing the same model with different heights shows that lateral displacement increases exponentially as the structure height increases. Increments in the number of storeys and applied axial load to the structure also affect lateral displacement [7].

P-Delta effects can be ignored based on the stability coefficient value. When lateral displacement has a higher value, the P-delta effect will be a must for consideration [8].

2.3 Structure Height

Structure height is one of the key components to indicate the inclusion of P-Delta effects during analysis. P-Delta effects influence even low-rise structures, but as the structural height increases, P-Delta effects get crucial for consideration [9].

To evaluate the necessity of P-delta inclusion in structure designing, the same structure with a different number of storeys shows that P-Delta effect has a direct but non-linear relation with structure height [10].

2.4 Lateral Stiffness

Structures with a higher lateral stiffness behave more toughly against lateral loads and have less deflection than a structure with lower lateral stiffness [11]. P-Delta analysis in high-rise RCC buildings equipped with shear walls and dumpers is another method of increasing lateral stiffness. Reinforced concrete buildings are subjected to lateral loads due to wind and earthquake which are governing factors especially, in high-rise and slender structures. To prevent lateral loads, the buildings are provided with lateral load-resisting systems. In regions where earthquakes are regular, structural and nonstructural parts and contents in high-rise buildings can suffer significant damage due to seismic loads. When the lateral load acts on a building, it causes deflections in its original shape. To minimize structural behavior towards lateral loads for high-rise buildings, it is suggested to increase the lateral stiffness of structure [12].

P-Delta effects exist in frames of any structure (Timber, RCC or Steel). Some factors may cause P-Delta to act more dominantly on frames. One of these factors is lateral stiffness which if incremented at an appropriate amount, can minimize P-Delta. It is worth mentioning that many other important factors have a huge effect on P-Delta inclusion in the analysis phase of structures. Some of these factors are eccentricity, seismic zone, geometric shape of a structure and axial loads applied to the frame [13].

2.5 Stability coefficient

P-Delta consideration may vary based on some factors for different structures. Studying each factor for different structures can be time consuming and problematic. The basic indicator for engineers to include P-Delta effects in the analysis phase of the structure is to determine the stability coefficient. This coefficient shows whether the P-Delta effect is crucial in the structure or not. If the stability coefficient is ≤ 0.1 then P-Delta consideration is not necessary [14].

$$\theta = \frac{P_X \, \Delta}{V_X \, h_{S\,X} \, C_d} \qquad [15]$$

Where;
P_x = The total vertical design load at and above Level x. (kip or kN); when computing P" no individual load factor needs exceed 1.0;
Δ = the design story occurring simultaneously with V" (in. or mm);
V_x = the seismic shear force acting between Levels x and x-1, (kip or kN);
$h_{s\,x}$ = the story height below Level x, (in. or mm);

C_d = the deflection amplification factor

3. Methodology

3.1 Research Type and Method

The current study is analytical and quantitative research on the P-Delta effect as per American standards. A total of five models are analyzed using CSI-ETABS software with response spectrum method to pinpoint the exact height at which P-Delta effects commence.

To evaluate the influence of shear walls on P-Delta effects, a moment resisting frame is modified by providing shear walls in appropriate positions.

3.2 Considered Models

- **Model-1:** A moment resisting frame without shear walls (G+9 storey with a story height of 3 m).
- **Model-2:** A moment resisting frame with shear walls (G+9 storey with a storey height of 3 m).
- **Model-3:** A moment resisting frame without shear walls (G+10 storey with a storey height of 3 m).
- **Model-4:** A moment resisting frame without shear walls (G+14 storey with a storey height of 3 m).
- **Model-5:** A moment resisting frame with shear walls (G+14 storey with a storey height of 3 m).

3.3 Structural Specifications

- The dimension of columns: $750\ mm \times 350\ mm$
- The dimension of Beams: $350\ mm \times 500\ mm$
- The slab thickness: $150\ mm$
- Dead load is 1.76 $^{kN}/_{m^2}$ and live load is 2 $^{kN}/_{m^2}$

- The concrete compressive strength is $30Mpa$
- Rebar tensile strength is $420Mpa$
- Seismic site class D
- Structure importance factor 1.25

3.4 The Load Combinations

- $1.4DL + 1.4LL$
- $1.2DL + 1.6LL$
- $1.3DL + 1.3LL + EX$
- $1.3DL + 1.3LL - EX$
- $1.3DL + 1.3LL + EPX$
- $1.3DL + 1.3LL + ENX$
- $1.3DL + 1.3LL + EY$
- $1.3DL + 1.3LL - EY$
- $1.3DL + 1.3LL + EPY$
- $1.3DL + 1.3LL + ENY$

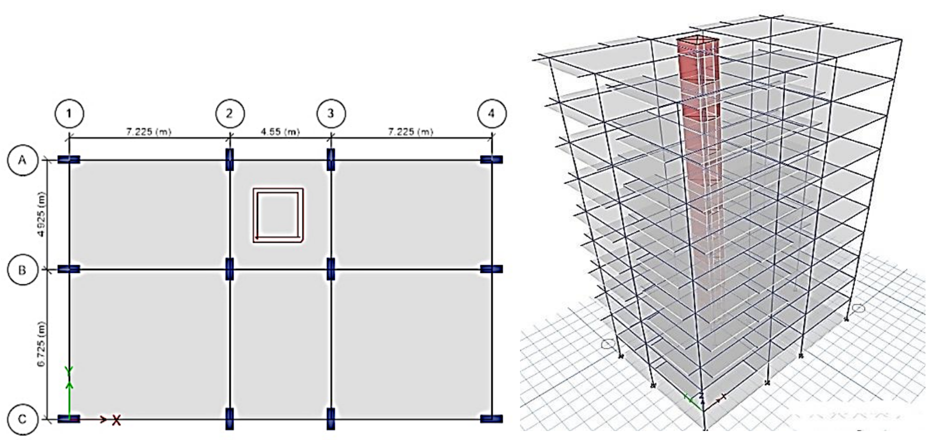

Figure 2: Model-1

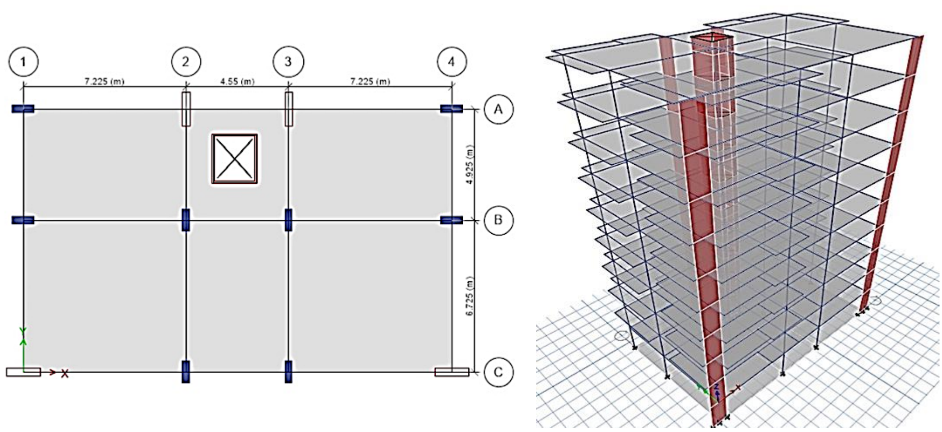

Figure 3: Model-2

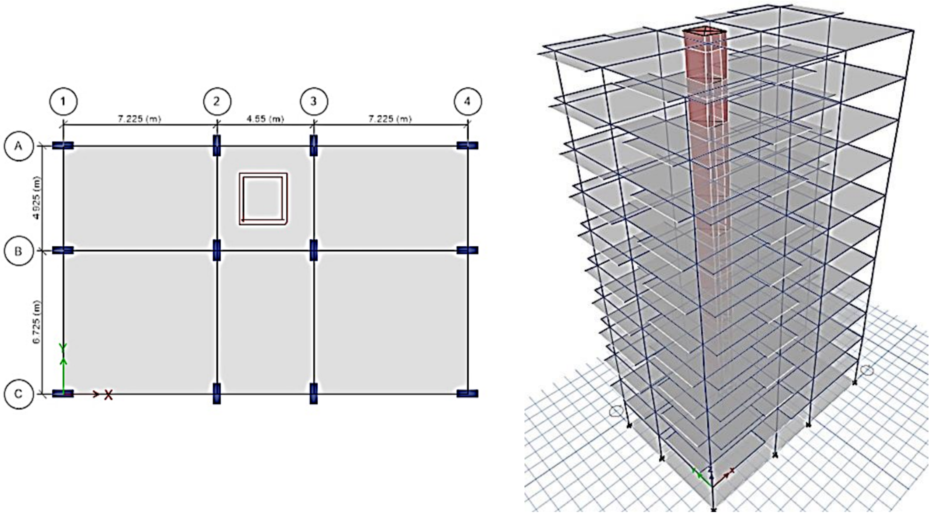

Figure 4: Model-3

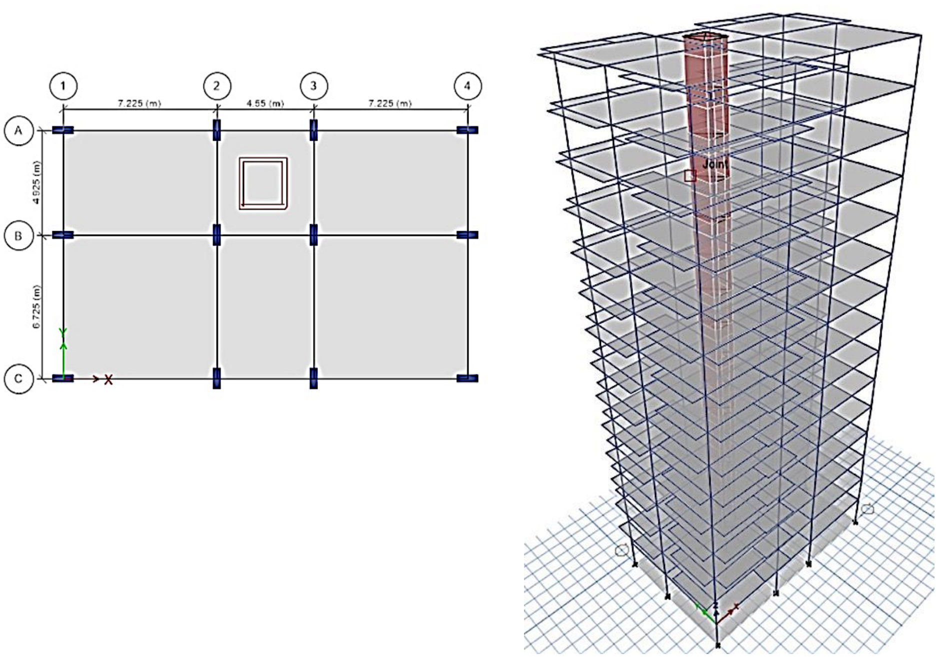

Figure 5: Model-4

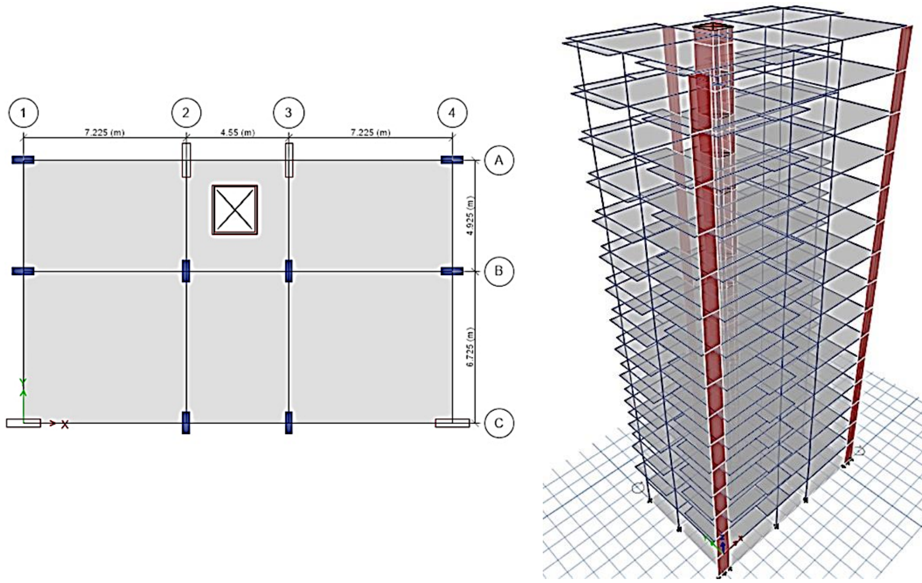

Figure 6: Model-5

4. Results and Discussion

Discussion has been done based on results for all five models considering stability coefficient, storey displacement and lateral stiffness as follows;

4.1. Stability Coefficient

Figure 7: Stability coefficient for models 1, 3, 4

Observing figure-7, it is clear that for a moment resisting frame without shear walls P-Delta is to be considered while analysing at a 33-meter height.

In figure-7, it is observed that height is not the only factor affecting P-Delta, since the stability coefficient which is the key indicator of P-Delta is not the same for models 1 and 4. Axial and lateral loads are also incremental factors of the P-Delta effect.

Figure-7 shows as the number of storeys increase same structure gets more unstable due to lateral load. While the stability coefficient for G+9 at storey 9 is 0.09, the value is increased by 67% for the same storeys in the G+14 building. This is the first indicator that as the number of the storeys increase the severity of P-Delta is visible. It is also worth mentioning that for the G+9 P-Delta is not considered in the calculation since the stability coefficient is not of the desired value. Therefore, the excluding of P-Delta can be another factor for the stabilized state of G+9. An additional weight of 50% live load and 120% dead load is considered during the calculations of P-Delta effects that can be another destabilizing factor for the G+14 model.

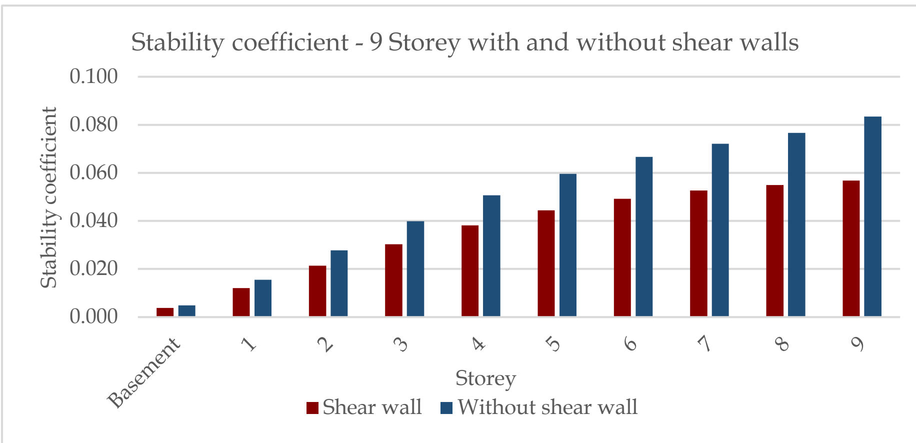

Figure 8: Stability coefficient for models 1 and 2

In figure-8, it is observed that although the number of storeys and applied loads on buildings are the same, the structure without shear wall has a higher value of stability coefficient since the frame is a moment-resisting without shear walls and the lateral stiffness shown in figure-12 for model 1 is not a noticeable amount. There is a 35% increase in stability coefficient of moment-resisting frames without shear walls while a structure with a shear wall has a much lower value due to its high lateral stiffness. The lateral stiffness for the shear wall frame system is 47% more than the moment resisting frame with shear walls.

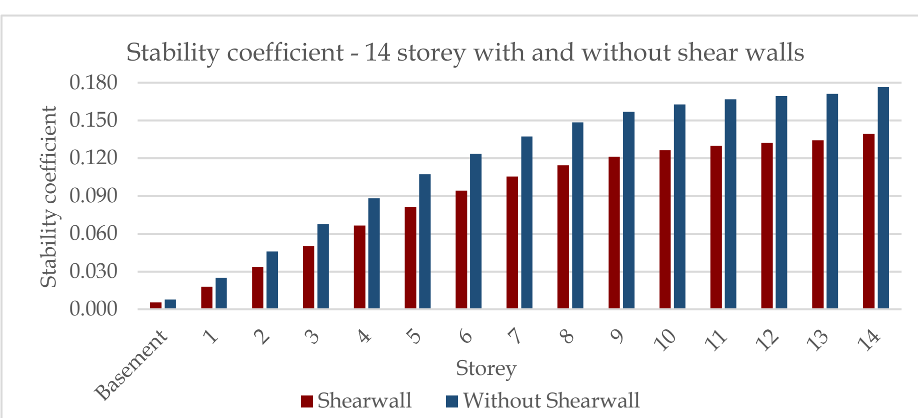

Figure 9: Stability coefficient for models 4 and 5

As shown in figure-9, it is observed that the stability coefficient for moment resisting frame is more severe. Although, it might have been predicted from the 10 storeys stability coefficient that the structure can be stable for almost 25 storeys but, as the stability coefficient's relation with storey height is non-linear, then prediction is never a good option. This phenomenon shows the non-linear relation between the stability coefficient and building height.

4.2. Lateral Displacement

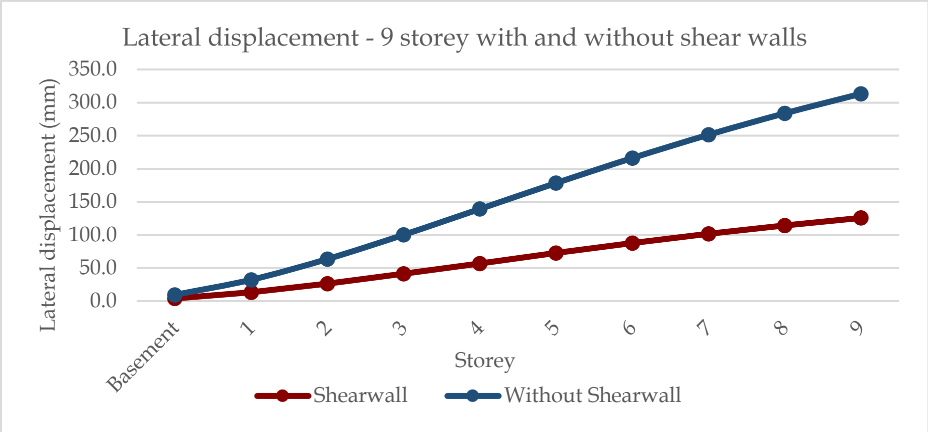

Figure-10: Lateral displacement for models 1 and 2

In figure-10, a significant change has been observed in lateral displacement. Since displacement is directly related to structure ductility and meanwhile shear wall is much more tough and brittle than moment resisting frame, the displacement has a 160% increment in moment resisting frame while the displacement in both cases is observed to be within the allowable range and does not risk the life of the occupants. The shear wall frame is safer and sounder. Considering the displacement values, lower displacement would not cause too much panic during an earthquake.

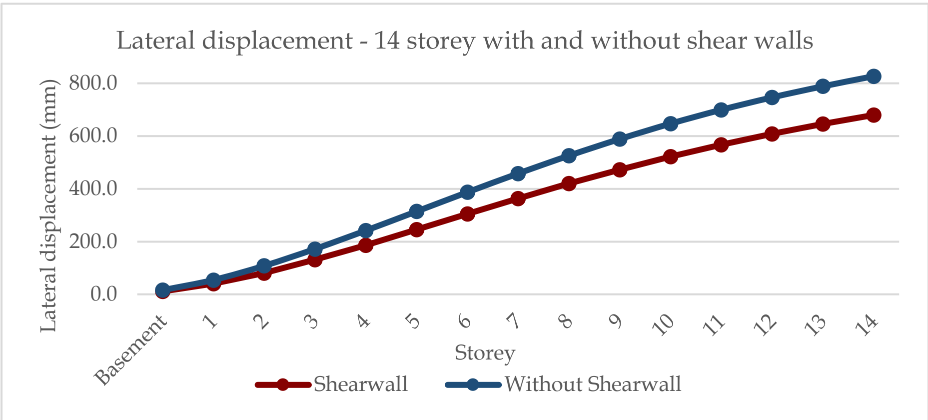

Figure 11: Lateral displacement for models 4 and 5

Figure-11 indicates that one of the biggest reasons to assume model 4 is not safe for the occupants, is the lateral displacement values. Since storey drift has a limitation for each type of moment-resisting system, it is observed that the storey drift value is not within the permissible limit for most of the storey. The shear wall frame has 20% less lateral displacement due to its high lateral stiffness.

Another point taken into consideration in this research is to study the difference in lateral displacements not only between structures with and without shear walls but, also between structures with the same frame systems and a different number of storey. The results of this comparison show the effects of axial loads or structure weight on the lateral displacement which is a key component in triggering the P-Delta effects.

4.3. Lateral Stiffness

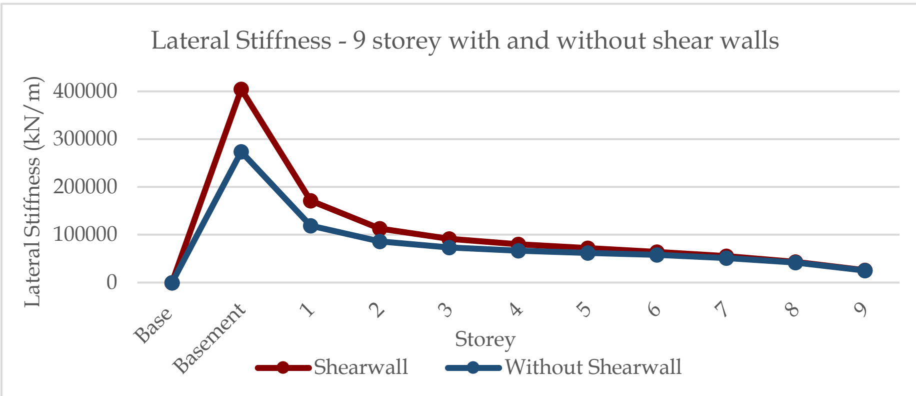

Figure 12: Lateral stiffness for models 1 and 2

Since the parent phenomenon for minimizing P-Delta in this study is to consider the increment of lateral stiffness by providing shear wall for the frame. From figure-12, it is observed that a 47% increment in lateral stiffness can cause a 160% decrease in lateral displacement and 45% decrease in stability coefficient.

In this article to reduce P-Delta effects, lateral stiffness is incremented practically, since the stiffer a structure gets the lower its overturning moment will be. Lower overturning moment causes triggering another destabilizing and failure factor to the structure, so lateral stiffness is increased practically while considering the decrease in overturning moment.

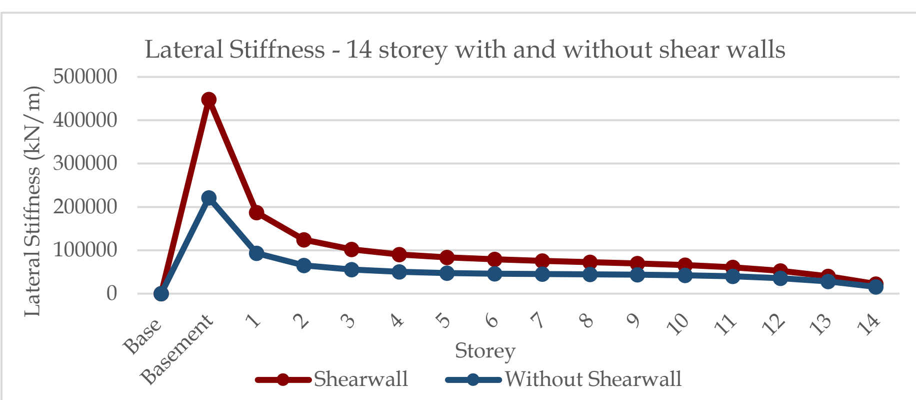

Figure 13: Lateral stiffness for models 4 and 5

Lateral stiffness is one of the key solutions for minimizing P-Delta effects. As shown in the figure-13, shear wall frame has almost twice the lateral stiffness than moment resisting frame without shear walls and the effects are clearly visible in the stability coefficient which has a decrease of 25% and lateral displacement with a decrease of 20%.

5. Conclusion

P-Delta effects or second-order effects are one of the phenomena that cause structural failure if not considered during analysis failure. This phenomenon applies an additional load on the structure due to lateral displacement and height increment. Stability coefficient determines if the P-Delta inclusion is necessary during structural analysis or not. If it is observed that P-Delta has significance in the structure then, lateral stiffness increment is a safe option to consider for minimizing P-Delta effects. Structure height, lateral (Seismic) load, lateral stiffness and lateral displacement have a significant influence on P-Delta effects.

- Axial load increment is also an imperative factor in the P-Delta effect.
- While P-Delta is a phenomenon which exists in any building at any height, however, it does not have its significance until the stability coefficient is ≥ 0.1 and since Afghanistan falls under the seismic Zone-D, it is important to check the stability coefficient at 30m height.
- One of the suitable ways to minimize P-Delta effects is the increment of lateral stiffness.
- There is a variety of options through which we could increase lateral stiffness. The most usual method used in Kabul city is shear wall placement.
- It is also worth mentioning to consider the stiffness of shear walls because a brittle structure will fail more severely than a ductile one.

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About the Authors

Mr. Ahmad Baset Popal, *Alumni, Department of Civil Engineering, and Member Research Society Kardan University, Kabul, Afghanistan.* <*basetpopal77@gmail.com* > ORCID: 0009-0000-3934-8635

Mr. Zabihullah Dalil Shinwari, *Lecturer, Faculty of Engineering, Kardan University, Kabul, Afghanistan.* <*z.shinwari@kardan.edu.af*> ORCID: 0009-0009-0344-6589

Mr. Iqbal Irshad, *Alumni Department of Engineering, and Member Research Society Kardan University, Kabul, Afghanistan.*

Mr. Abdul Sattar Nawabi, *Alumni, Department of Civil Engineering, and Member Research Society Kardan University, Kabul, Afghanistan.*

Mr. Sayed Javid, *Alumni, Department of Civil Engineering, and Member Research Society Kardan University, Kabul, Afghanistan.*