Seismic response of multi-storey reinforced concrete buildings with soft floor

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\textbf{ABSTRACT}

The high-rise building in which ground storey consists of open space is known as building with soft floor. Such floor plays an important role in seismic performance of the building. This is due to the abrupt changes in lateral stiffness and strength caused by such storey.

In this study, the seismic performance of RC buildings with soft storey using finite element method is investigated. The parameters considered in this research include the height of soft storey, irregularity in building plan dimensions, and the location of soft storey along the building height. An attempt is made in this research to find the optimum location of the soft storey through the building height to minimize its effect. In addition, the impact of applying simple strengthening techniques is investigated to promote structural safety without significant changes in the architectural and functional requirements of the building. The results include the effect of the investigated parameters on stiffness, displacement and storey drifts by using equivalent static load method and modal response spectrum method (MRS). P-Delta effect and cracked stiffness ratio are included in analysis.

The results show that the factors such as increasing height of soft storey or increasing length-to-width ratio in the building have a significant effect on the stiffness and resistance. The results also demonstrate the effectiveness of the presence of shear walls for increasing stiffness and reducing displacements. Besides, providing a bracing system for retrofitting the building with soft storey has a positive effect on the behavior of these buildings.

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\section*{Introduction}

Most of multi-storey buildings require open storey for parking, retail shops, meeting rooms, etc., which is called Soft-Storey. As shown in Figure 1, the main problem that confronts structural engineers is that presence of the soft storey

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Figure 1. Examples of collapse in building with soft storey [23,24].
causes structural irregularity in terms of stiffness and strength. Therefore, determination of the soft-storey requirements and its effects on the building are essential in the design process to predict the seismic performance of high-rise buildings. This study includes implementing a parametric study on bare frame and shear wall systems due to increasing height of soft storey, changing length-to-width ratio (L/W), increasing load in soft storey with different levels, and changing bracing arrangement in buildings with soft storey.

Many studies have focused on the effect of masonry infill wall, and effect of changing the level of soft storey along the building height. However, limited research efforts were made to investigate the seismic performance of buildings with soft storey considering the above parameters.

**Code provisions and literature review**

In international building design codes, the soft storey specifications are presented as the following:

- ASCE (2010) [1], IS (2016) [2], and UBC-97 [3] define the soft-storey irregularities as follows:
  
  (a) Normal Soft storey: occurs when lateral storey stiffness is less than 70% of the stiffness of the storey above it or less than 80% of the average stiffness of the above three stories; which is defined by the following formula:

  \[ k_i < 0.7k_{i+1} \rightarrow \text{Softstorey} \]  

  or

  \[ k_i < 0.8 \frac{k_{i+1} + k_{i+2} + k_{i+3}}{3} \rightarrow \text{Softstorey} \]  

  where, \( k_i \) the lateral storey stiffness

(b) Extreme Soft storey: occurs when lateral storey stiffness is less than 60% of the stiffness of the storey above or less than 70% of the average stiffness of the above three stories.

- Japanese Seismic Code (2011) [4] presents the soft-storey irregularities as shown in Equation (3). Lateral stiffness ratio \( R_s \) of each storey (except the basement) shall be equal to or greater than 0.6

  \[ R_s = \frac{r_s}{r_s^c} \geq 0.6 \text{ if } R_s < 0.6 \rightarrow \text{Softstorey} \]  

  Where, \( r_s \) is the lateral stiffness, which is defined as the story height divided by the story drift caused by the lateral seismic shear for moderate earthquake motions, and \( r_s^c \) is the mean lateral stiffness that is defined as the arithmetic mean of \( r_s' \)’s.
• Turkish code (2007) [5] states that soft storey occurs when stiffness irregularity factor \( \eta_{ki} \) is greater than 2.0. This factor is calculated by the following two equations:

\[
\eta_{ki} = \frac{\Delta_i}{h_i} \frac{(\Delta_i+1)}{h_{i+1}} > 2.0 \rightarrow \text{Softstorey} \tag{4}
\]

Or

\[
\eta_{ki} = \frac{\Delta_i}{h_i} \frac{(\Delta_{i-1})}{h_{i-1}} > 2.0 \rightarrow \text{Softstorey} \tag{5}
\]

where, \( \Delta_i \) is the storey drift and \( h_i \) is the height of storey, \( \eta_{ki} \) is the ratio of the average relative storey drift at any \( i \)th storey to the average relative storey drift at the storey immediately above or below.

N. Khanal et al. (2019) [6] discussed the comparisons between various codes for building with soft storey and the effect of change in the height of soft storey was taken into consideration.

Several studies have been done by many researchers to investigate the seismic performance of soft storey building.

Jaswant et al. (1997) [7] discussed the errors taking place when modeling the building as a complete bare frame and ignoring the impact of infill walls. Results indicated that the presence of the infill wall dissipated more energy than a bare frame system. In this approach, the drift and natural period increased while stiffness decreased in the bare frame case compared to other models. Robin Davis et al. (2004) [8] and Saraswati and Vineet (2012) [9] studied different models, bare frame building with soft storey, infill wall in upper floors, a shear wall at the core, and increased column stiffness. As far as the findings were concerned, the existence of soft storey in building decreased the base shear and increased the abrupt change in drift. They suggested that the soft-storey building needed to be retrofitted to sustain the loss of the infill wall. Sharany and Khan (2009) [10], Oman et al. (2017) [11], and Charan and Mahadev (2017) [12] investigated the effect of increasing the percentage of infill walls in soft storey buildings. The results indicated that neglecting the infill wall in design of building with soft floor resulted in base shear and moment to become twice the actual values. Nurjaman et al. (2012) [13] carried out experimental and theoretical investigation on four various precast specimens. The results showed that the increase in stiffness when retrofitting existing buildings by applying concrete walls in corners of a building would avoid the soft storey effect. Similar to the researches mentioned above (K.Vamsi and Vinodh, 2016 [14]; Mohammad and V. R., 2014 [15];Devendra et al., 2019 [16]; Krishna et al .,2020 [17]), the presence of infill wall decreases the drift and displacement. Therefore, it was suggested that at least soft storey should be provided with outer masonry infill to increase stiffness. Furthermore, adding shear wall or increasing the column stiffness increased the base shear and frequency of building.
Other researchers discussed the effect of presence of soft storey at different levels (Amit, 2012 [18]; Rahiman and Prof. M. R., 2013 [19]; Ranjit, 2015 [20]; Achyut, 2018 [21]; M. Uzun, 2018 [22]). The results showed that putting soft storey at higher level results in a reduction of a number of hinges, which lead to an increase in base shear and a decrease in time period.

At present, the majority of researches focus on the effect of masonry infill wall, and effect of level of soft storey along the building height in multi-storey buildings. This research is devoted to investigate seismic performance as a result of changing different parameters and comparing it with seismic requirements in the design code. These include building length-to-width ratio, height of soft storey, and load on soft floor. Moreover, in this research the effect of using bracing system to strengthen buildings with soft storey is evaluated. The flow chart in Figure 2 illustrates the methodology in this study.

Case study

A high-rise building which consists of typical 20 storeys is used in this study. The building is located in Cairo zone. The height of each storey is 3 m with variable height for the first floor. The plan consists of five bays of 6.0 m each in both directions. The frame members are modeled with rigid end zones. Finite element method (FEM) program, ETABS 2016, is used for modeling the structure. Two seismic analysis methods (equivalent static load method and modal response spectrum method (MRS)) are performed. Rigid diaphragms are assigned to each floor. P-Delta effect and cracked stiffness ratio are included in analysis. General layout of the studied building is shown in Figure 3.

Concrete sections are designed to achieve the safe dimensions according to the UBC 97 code under static and dynamic loads. The thickness of solid slab with span 6 m is taken as 200 mm, the minimum wall cross section under dynamic loads is 0.3 × 6.0 m and the walls will continue with this section in all floors. the cube compressive strength of concrete (Fcu) is 30 MPa and yield strength of steel reinforcement is 360 MPa.

The flooring cover, uniform wall load and uniform live load are assumed to be 1.5 kN/m², 1.5 kN/m², and 2.0 kN/m², respectively. For seismic loads, seismic zone is assumed to be 2A with peak ground acceleration = 0.15 g. Soil type is assumed to be type stiff soil (SD)with shear wave velocity of 180–360 m/s and the response modification factor equals 5.5.

Description of case studies

This study investigates the soft storey effect when changing some parameters arranged in different groups. The study is divided into seven groups with
Figure 2. Research methodology flow chart
three or four cases for each group. These groups investigate the effect of increasing height of soft floor, irregularity in plan due to change in length-to-width ratio at different heights of soft floor and effect of changing soft storey levels with increasing loads on soft floor. First, moment resisting frame system (MRF) is applied in each case. Second, shear wall (SW) was added to the seven previous groups for studying the change in relative stiffness after adding shear wall. Shear wall is located at the center of the building (core wall). The layout of the studied building with shear wall is shown in Figure 4. Each case has a designation beginning with MRF or SW followed by the group number; following is a numerical designation indicating the case number. For example, MRF-3-4 represents that this structure is the fourth case in the third group. Expansion joints are neglected in the design, therefore, the effect of temperature is not taken into consideration. The description of all groups is shown in Table 1. All studied models are taken seismic requirements into the design, and results are compared to the allowable values in ubc97 code.

For investigating the optimum position and bracing ratio to be added for retrofitting of building with soft storey, two additional groups of different height in soft floor (6 m and 8 m) were studied. The bracing arrangements include six cases as shown in Table 2 and Figure 5. After investigating the optimum position and bracing ratio to be added for retrofitting of building with soft storey, bracing was applied in nine models using shear wall system. Retrofitted models have a designation beginning with BS followed by the group number; following is a numerical designation indicating the case number. For example, BS-1-4 represents a structure with bracing system as the fourth case in the first group. These models are presented in Table 3.
**Figure 4.** Layout of the studied building with SW.

| Models   | Soft storey height (m) | L/W ratio | Area (m × m) | Soft storey level |
|----------|------------------------|-----------|---------------|-------------------|
| MRF-1-1  | 4                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-1-2  | 6                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-1-3  | 8                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-2-1  | 4                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-2-2  | 4                      | 2         | 30×60         | First floor (1<sup>st</sup>) |
| MRF-2-3  | 4                      | 3         | 30×90         | First floor (1<sup>st</sup>) |
| MRF-2-4  | 4                      | 4         | 30×120        | First floor (1<sup>st</sup>) |
| MRF-3-1  | 6                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-3-2  | 6                      | 2         | 30×60         | First floor (1<sup>st</sup>) |
| MRF-3-3  | 6                      | 3         | 30×90         | First floor (1<sup>st</sup>) |
| MRF-3-4  | 6                      | 4         | 30×120        | First floor (1<sup>st</sup>) |
| MRF-4-1  | 8                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-4-2  | 8                      | 2         | 30×60         | First floor (1<sup>st</sup>) |
| MRF-4-3  | 8                      | 3         | 30×90         | First floor (1<sup>st</sup>) |
| MRF-4-4  | 8                      | 4         | 30×120        | First floor (1<sup>st</sup>) |
| MRF-5-1  | 4                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-5-2  | 4                      | 1         | 30×30         | Middle floor (11<sup>th</sup>) |
| MRF-5-3  | 4                      | 1         | 30×30         | Roof floor (20<sup>th</sup>) |
| MRF-6-1  | 6                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-6-2  | 6                      | 1         | 30×30         | Middle floor (11<sup>th</sup>) |
| MRF-6-3  | 6                      | 1         | 30×30         | Roof floor (20<sup>th</sup>) |
| MRF-7-1  | 8                      | 1         | 30×30         | First floor (1<sup>st</sup>) |
| MRF-7-2  | 8                      | 1         | 30×30         | Middle floor (11<sup>th</sup>) |
| MRF-7-3  | 8                      | 1         | 30×30         | Roof floor (20<sup>th</sup>) |
Table 2. Investigation groups for selecting optimum position and bracing ratio.

| Case 1     | Bare frame with soft storey |
| Case 2     | Bracing at soft floor only  |
| Case 3     | Bracing at the center bays only |
| Case 4     | Bracing at some vertical bays from second floor to top |
| Case 5     | Bracing at all bays from second floor to top |
| Case 6     | Bracing in all bays          |

Figure 5. Elevation of various bracing arrangement for all cases.
Table 3. Groups selected for retrofitting by adding bracing in soft floor.

| SW system | Soft storey height (m) | L/W ratio | Area (m) | Soft storey level |
|-----------|------------------------|-----------|----------|------------------|
| BS-1-4    | 8                      | 1         | 30*30    | First floor (1st) |
| BS-4-1    | 8                      | 1         | 30*30    | First floor (1st) |
| BS-4-2    | 8                      | 2         | 30*60    | First floor (1st) |
| BS-4-3    | 8                      | 3         | 30*90    | First floor (1st) |
| BS-4-4    | 8                      | 4         | 30*120   | First floor (1st) |
| BS-6-2    | 6                      | 1         | 30*30    | Middle floor (11th) |
| BS-7-1    | 8                      | 1         | 30*30    | First floor (1st) |
| BS-7-2    | 8                      | 1         | 30*30    | Middle floor (11th) |

Results

The following sections show the effect of different parameters on lateral displacement, drift, and relative stiffness of buildings with soft floors. All results show in horizontal direction (X) according to seismic loads.

Effect of height of soft floor

Figure 6(a) shows the effect of height increase of soft storey on the lateral displacement of the building. Comparing the plotted curve in horizontal direction (X) according to seismic loads shows that: the maximum displacements occur at top floor when height of soft storey increases from 4 m to 8 m. The maximum displacements are 284.5, 294.3, and 308.5 mm for models H soft = 4, 6, and 8 m, respectively. The decrease in displacements at top floor when H soft = 4 and 6 m is 7.8% and 4.6%, respectively, compared to H soft = 8 m.

Figure 6(b) shows the storey drifts due to height increase of soft storey. The presence of soft storey in RC building causes a sudden change in storey
drifts at soft storey level. The storey drifts at first floor for height of soft storey of 4 m, 6 m, and 8 m is 9.0 mm, 19.5 mm, and 34.6 mm, respectively. The decrease in storey drifts at height of 4 and 6 m is 74.1% and 43.7%, respectively, compared to \(H_{\text{soft}} = 8\) m. In case of \(H_{\text{soft}} = 4.0\) m, the storey drifts are achieved the seismic design requirements in code because in this case soft storey does not occur. But, when increasing the height of soft storey to 6 m and 8 m, the storey drift values exceed the allowable storey drift values in code.

**Effect of changing length to width ratio**

Figures 7, 8, and 9 clarify the effect of increasing length to width ratio of the building plan on the lateral displacements and drifts when height of soft storey varies as 4 m, 6 m, and 8 m. Figure 7(a) shows that the displacement decreases with increasing length to width ratio. The displacement values achieve the seismic requirements in code although increase the length to width ratio because soft storey does not occur. The maximum displacement is 284.5, 132.5, 69.2, and 50.9 at \(L/W = 1, 2, 3, \) and 4, respectively. Figure 7(b) shows that the storey drifts decrease with increasing length-to-width ratio. By comparing the results with seismic code limits, it is found that storey drifts achieve the storey drift limits in code, although \(L/W\) ratio increases.

Figure 8(a) compared with the displacement in Figure 6(a), the increase in height of soft storey from 4 m to 6 m increases maximum displacement to 294.3, 137.0, 71.7, and 52.7 mm. Figure 8(b) shows that the storey drifts decrease with increasing \(L/W\) ratio. By comparing the storey drift results

![Figure 7](image-url)  
**Figure 7.** Comparison of displacement and storey drift values for different \(L/W\) ratios at \(H_{\text{soft}} = 4\) m for Group 2 (MRF-2).
with allowable limits in design code, it can be observed that the storey drifts exceed the allowable values in code.

By observing the results from Figure 9(a,b) and comparing them with the previous results in Figure 7 and 8, this indicates that the storey drift deviation increases when soft floor height increases with increasing length-to-width ratio. In addition, the presence of soft storey with increasing L/W ratio has
a noticeable effect on the storey drift as it exceeds the permissible values in the code, which may lead to failure.

**Effect of increasing load in soft floor with different storey levels**

Figure 10 illustrates the displacement and drift values when taking into account the effect of increasing the load on the soft ground with different storey levels at $H_{\text{soft}} = 4$ m. The results are shown for building models with soft storey at First, middle ($11^{\text{th}}$), and roof floor ($20^{\text{th}}$) levels. The presence of soft-storey increases the displacement values of the stories above but does not affect the displacement values of the stories below. Figure 10(a) shows that there is no much change in lateral displacement values when putting the soft storey at different levels at $H_{\text{soft}} = 4$ m. However, the storey drifts have a noticeable effect when changing the level of soft storey as shown in Figure 10(b). The effect of irregularity does not appear in all the previously studied models at the height of $H_{\text{soft}} = 4$ m. However, when the soft floor was placed in the middle of the building, it had a significant effect on the decrease in stiffness and consequently the effect on the drift storey values at this floor.

Figure 11(a) and Figure 12(a) show that the maximum displacement is 321.4 mm and 350 mm, respectively, when soft storey is located at middle floor in X direction. The graph in Figure 11(b) and Figure 12(b) shows the maximum drift is 43.7 mm and 67.5 mm when soft storey is located at middle floor in X direction.

Comparing the results in X direction in Figures (10), (11), and (12) show that the minimum change in displacement at first floor occurs when the soft

![Figure 10](image.png)

**Figure 10.** Comparison of displacement and storey drift values for different soft storey levels at $H_{\text{soft}} = 4$ m for Group 5 (MRF-5).
storey is located at roof floor. Furthermore, it can be observed that the lateral displacement when soft storey at middle-floor is more than those for other levels. The maximum abrupt change of storey drift occurs when soft storey is located at (11th) floor compared to the other models so this case should consider in seismic design requirements.

**Figure 11.** Comparison of displacement and storey drift values for different soft storey levels at $H_{\text{soft}} = 6$ m for Group 6 (MRF-6).

**Figure 12.** Comparison of displacement and storey drift values for different soft storey levels at $H_{\text{soft}} = 8$ m for Group 7 (MRF-7).
Strengthening of RC building with soft storey by adding bracing in various arrangements (BS)

Different bracing arrangements were used to investigate the optimum arrangement of bracing, which can reduce the negative effects of soft storey. In this research, the bracing arrangements include six cases, as shown in Table 2 and Figure 4. The results of these cases are presented in the following sections.

Various bracing arrangements when H soft = 6 m (Group 8)

The lateral displacement and drifts of each floor is plotted in Figure 13 for the 6 cases of bracing arrangements. The results show that the maximum displacement in the X direction is (216.6 mm) at top floor in case 1, where no bracing is added. In case 6, where bracing is added in all floors, the displacement reached only 31.4 mm at top floor. In case 2, soft storey conditions are not valid; however, the displacement increased at top floor compared to other cases since the bracing is added only at the intended soft floor. The displacements at top floor in cases 2, 3, 4, 5, and 6 after adding bracing are 193.2 mm, 115.5 mm, 71.4 mm, 33.5 mm, and 31.4 mm, respectively. These results verify that bracings have a significant effect on reducing displacement.

The drift values are regular in case 2, where soft storey conditions are not valid. The maximum drift value is 16.3 mm taking place at first floor in case 1, where bracing is not added in the building. Drift values at first floor in cases 2,
Table 4. Relative stiffness for different arrangements of bracing at H soft = 6 m in both directions.

| Storey No | case1 | case2 | case3 | case4 | case 5 | case 6 |
|-----------|-------|-------|-------|-------|--------|--------|
| 2(X)      | 1.13  | 1.42  | 1.09  | 0.88  | 0.72   | 1.00   |
| 1(X)      | 0.87  | 2.04  | 0.79  | 0.45  | 0.31   | 0.64   |
| 2(y)      | 0.94  | 1.33  | 1.05  | 0.75  | 0.59   | 1.02   |
| 1(y)      | 0.50  | 4.06  | 0.56  | 0.13  | 0.08   | 0.53   |

3, 4, 5, and 6 are 4.4 mm, 8.1 mm, 9.2 mm, 8.4 mm, and 3.1 mm, respectively. These results show that the drift has the lowest value in case 6, where bracing is added to all floors. However, this solution is not economically viable.

As seen in Table 4, the relative stiffness for case 1 (bare frame) in the Y direction is less than 70%. Hence, soft storey conditions are valid at first floor in Y direction. Due to decreased stiffness in case 1, bracing is added with different arrangements for all other cases. In case 3, the relative stiffness is less than 70% in Y direction indicating soft storey case in first floor. In cases 4 and 6, the relative stiffness is less than 70% in X direction and less than 60% in Y direction indicating soft storey case in first floor. The critical situation occurs in case 5, where bracing is added on all floors except first floor. The relative stiffness in this case is less than 40% in X direction, less than 10% in first floor, and 60% in second floor in Y direction indicating soft storey. In case 2, where bracing is added in first floor only, the relative stiffness is more than 70% in both directions indicating no soft storey. Case 5 and Case 6 are studied for comparison purposes only, although they are not economically viable.

Various bracing arrangements when H soft = 8 m (Group 9)

The results in Figure 14 show that the displacement and drift values increase when the soft storey height increases from 6 m to 8 m. As shown in Table 5, the relative stiffness in Case 4 and Case 5 become more critical than those from eighth group because soft storey occurs at first and second floors. This indicates that the position and ratio of bracing must be located accurately to get the best response during earthquakes.

The results of groups 8 and 9 with different arrangements of bracing, it can be concluded that the most effective position of bracing is that in case 2 when the bracing is added in soft floor only. Although soft storey conditions are not valid when adding bracing, the displacement is increased at the top floor, because the bracing is added at first floor only. Therefore, it is clear that the effect of adding bracing in soft floor only causes significant improvement in the relative stiffness.
Summary of analytical results

Building stiffness is the main property affected by the presence of a soft floor according to several codes. The finite element program ETABS –2016 software was used to study the effect of different parameters on the seismic performance of buildings with soft storey. These parameters include height of soft storey, level of soft storey along the building height, length-to-width ratio of the building, and the use of bracing to strengthen the building. The results of this research include the effect of these parameters on the building stiffness, displacement and storey drifts. The results show that the presence of soft storey in a building, especially in the middle height of the building, significantly reduces the building stiffness. The results of this research may help design engineers in taking the soft storey problem into account in their design practice. The results of all groups of this study are summarized in Table 6, Figure 15, and Figure 16.

For moment resisting frame (MRF) groups, the results show that the presence of soft storey induces sudden change in displacement, storey drift, and stiffness. Increasing the soft storey height can cause significant decrease in relative stiffness between floors. The results clearly indicate that the abrupt change in storey

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**Figure 14.** Displacements and drifts of RC building with soft floor for different arrangements of bracing at H soft = 8 m.

**Table 5.** Relative stiffness for different arrangements of bracing at H soft = 8 m in both directions.

| Storey No | case1 | case2 | case3 | case4 | case5 | case6 |
|-----------|-------|-------|-------|-------|-------|-------|
| 2 (x)     | 1.04  | 1.37  | 1.03  | 0.81  | 0.64  | 0.97  |
| 1 (x)     | 0.56  | 1.48  | 0.51  | 0.27  | 0.18  | 0.40  |
| 2 (y)     | 0.87  | 1.30  | 1.03  | 0.66  | 0.51  | 1.02  |
| 1 (y)     | 0.29  | 2.67  | 0.34  | 0.07  | 0.04  | 0.33  |
### Table 6. Relative stiffness for all groups by using MRF, SW and BS systems.

| Groups | Cases | MRF | SW | BS |
|--------|-------|-----|----|----|
|        |       | $k_i$ (x) | $k_i$ (y) | $k_i$ (x) | $k_i$ (y) | $k_i$ (x) | $k_i$ (y) |
| 1      | 1     | 1.56 | 1.09 | 1.45 | 1.29 | 1.09 | 1.29 |
|        | 2     | 0.86 | 0.5  | 0.84 | 0.85 | 0.85 | 0.85 |
|        | 3     | 0.56 | 0.28 | 0.57 | 0.64 | 0.9  | 0.86 |
| 2      | 1     | 1.56 | 1.09 | 1.45 | 1.29 | 1.09 | 1.29 |
|        | 2     | 1.54 | 1.09 | 1.41 | 1.30 | 1.3  | 1.26 |
|        | 3     | 1.49 | 1.06 | 1.3  | 1.26 | 1.26 | 1.22 |
|        | 4     | 1.49 | 1.06 | 1.26 | 1.22 | 1.26 | 1.22 |
| 3      | 1     | 0.86 | 0.5  | 0.84 | 0.85 | 0.85 | 0.85 |
|        | 2     | 0.85 | 0.5  | 0.83 | 0.77 | 0.77 | 0.77 |
|        | 3     | 0.81 | 0.48 | 0.77 | 0.77 | 0.77 | 0.77 |
|        | 4     | 0.81 | 0.48 | 0.74 | 0.69 | 0.74 | 0.69 |
| 4      | 1     | 0.56 | 0.28 | 0.57 | 0.64 | 0.9  | 0.86 |
|        | 2     | 0.55 | 0.28 | 0.56 | 0.51 | 0.96 | 1.16 |
|        | 3     | 0.51 | 0.26 | 0.52 | 0.56 | 0.94 | 1.2  |
|        | 4     | 0.51 | 0.26 | 0.50 | 0.43 | 0.96 | 1.35 |
| 5      | 1     | 1.57 | 1.1  | 1.45 | 1.29 | 1.1  | 1.29 |
|        | 2     | 0.75 | 0.68 | 0.81 | 0.82 | 0.68 | 0.82 |
|        | 3     | 1.55 | 1.53 | 1.74 | 1.77 | 1.53 | 1.77 |
| 6      | 1     | 0.87 | 0.5  | 0.84 | 0.86 | 0.86 | 0.86 |
|        | 2     | 0.47 | 0.35 | 0.53 | 0.54 | 0.73 | 0.68 |
|        | 3     | 2.54 | 3.01 | 2.66 | 2.7  | 2.66 | 2.7  |
| 7      | 1     | 0.56 | 0.28 | 0.57 | 0.64 | 0.91 | 0.86 |
|        | 2     | 0.33 | 0.22 | 0.38 | 0.41 | 0.56 | 0.52 |
|        | 3     | 3.63 | 5.09 | 3.62 | 3.64 | 3.62 | 3.64 |

Relative stiffness ($k_i$) is calculated by divided (storey stiffness/storey stiffness of floor above) = ($k_i/k_{i+1}$) for each storey in two directions (x and y).
drift and displacement increases when soft storey height increases. On the other hand, when L/W ratio increased, the soft storey irregularity in stiffness increased. The maximum displacement, and storey drift occurred when (L/W = 1) as compared to other ratios. Momentous effect on results occurred when increasing the soft storey height with increasing L/W ratio. The shift of soft storey to higher-level affected the seismic performance. The results show that the worst-case occurred when soft storey level is in the middle floor.

Table 6 shows that adding shear wall, as a lateral supporting system significantly improve the relative stiffness for all groups. Although soft storey height
increases from 3 to 6 m, soft storey conditions do not occur after adding shear wall as compared to MRF system. Even though adding the shear wall improved the hardness, it was unable to repeal the effect of the soft floor at an altitude higher than double the height of the repeated floor. The presence of the soft floor at middle of the building height is still the worst case despite the addition of the shear wall.

After adding bracing (BS system) at soft floor only with SW system, every soft storey existing problem, which was solved by adding bracing at soft floor except model in group 6 in addition to group 7 where soft storey is at middle level. The results indicate that the worst case in building with soft floor exists when soft floor is located at middle level. Retrofitting the building by adding bracing has a noticeable improvement in the relative stiffness.

**Conclusions**

This paper aims to investigate seismic performance as a result of changing different parameters and comparing it with seismic requirements in the design code. These include building length to width ratio, height of soft storey and load on soft floor. Moreover, in this research the effect of using bracing system to strengthen buildings with soft storey is evaluated. The results of static and response spectrum analysis taking into account the effect of soft storey in reinforced concrete buildings are presented in this research. Based on the results of the studied building groups, the following points can be drawn:

- The current formula of the code based on taking the effect of the height in the soft floor into account, but it does not specify the permissible limits in height and the precautions that must be taken into account when increasing the height of the soft floor. The study results showed that when the height of the soft floor is equal to or more than twice the height of the typical floor, the results of displacement and storey drifts are greater than the permissible limits in the code. Therefore, if necessary, retrofitting systems such as bracing system on this floor should be used to reduce the effect of soft floor irregularities.
- Length to width ratio should be considered in code formula for estimating the ratio to it is being compared with the relative stiffness in design code. When (L/W) ratio increases from 1 to 4, the maximum displacement ratio decreases by 82%, and the drift decreases by 79% for MRF system. In addition, soft storey height must be considered when the L/W ratio exceeds 4 since it leads to high soft storey irregularity.
- Change in soft storey level should be considered in code formula for estimating the ratio to it is being compared with the relative stiffness in design code. Design equations are based on the soft floor level is on the first floor, but no limits were mentioned for changing the soft floor level,
although it has a significant effect on the structural response. By comparing the presence of soft storey in different locations, the results show that the worst-case occurs when soft storey is located at middle floor as compared to other levels. The maximum value of displacement and maximum sudden change in drifts occur when shifting the soft floor level near to mid-level of RC building.

- Shear walls are found to be very effective in improving the stiffness irregularity and decreasing the displacement and drift. For example, after adding a shear wall with increasing soft storey height, the displacement decreases by 46% while the drift decreases by 60% at soft storey height equal to 6 m as compared to MRF system. Despite adding the shear wall, the effect of the soft storey is still present when soft storey height is greater than twice the height of typical floor.

- Cross bracing is found to be very effective and economical technique for retrofitting building with soft storey and reducing the stiffness irregularity. Determining the position and ratio of bracing is very important to improve the seismic performance of RC building with soft floor. On the other hand, adding the bracing only at soft storey is the best solution to reduce the soft storey irregularity. Adding cross bracing, the effect of soft storey was greatly reduced in most study groups despite increasing displacement and drifts.

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