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Investigation of soft storey action of a reinforced concrete building by pushover analysis

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Abstract. Soft storey action is a common type of vertical stiffness irregularity encountered in earthquake sites. There are different code-defined approaches in terms of determining the presence of soft storey irregularity. Türkiye Building Earthquake regulation (TBDY-2018) requires the stiffness irregularity coefficient determined by the ratio of adjacent storey drift ratios to be greater than 2 to validate this irregularity. As for the American Society of Civil Engineers regulation (ASCE/SEI-7-10), the extreme soft storey is valid if lateral storey stiffness is smaller than 60% of the neighbourhood storey or 70% of the average of the 3 above storeys. As for Japanese regulation, the ratio of the inverse of the drift ratio to the average of the inverse of the drift ratios along all storeys is lower than 0.6. In this work, these stiffness irregularity parameters are calculated and compared with their limit value, both elastic and inelastic behavior of a 3D reinforced concrete frame system with ground storey height greater than other storeys. The variation of the effect of stiffness irregularity while continuing inelastic behavior is investigated by gradually increasing top displacement. The storey drifts, drift ratios, storey shear and stiffness irregularity factors of TBDY-2018, ASCE and Japanese regulations are calculated for all nonlinear pushover steps. The pushover curve and the values of stiffness irregularity factors in terms of top displacement are plotted. As a result of 2% top drift ratio, values of factors of inelastic analysis are obtained as 4-5 times of elastic analysis result.

Keywords: Soft storey; Stiffness irregularity factor; Pushover analysis; Reinforced concrete; Nonlinear modeling

1. Introduction

Soft storey action or interstorey stiffness irregularity is one of the most frequently encountered irregularity problem in earthquake sites, which may result in the collapse of buildings. "*Many failures and collapses can be attributed to the increased deformation demands caused by soft stories*" (Bruneau, 2002). The problem of structural collapse due to soft story irregularity is a phenomenon that can be observed not only in Türkiye. "*Similar damage patterns as a result of soft storey were found in earthquakes in other areas of the world*" (Sharma et al, 2016). As declared in Zhao et al, 2009; "*the data collected in the field shows that most of the reinforced concrete building frames did not perform as intended by the current Chinese code: most failures developed at the columns, either through shear failure or through excessive deformation demands at the ground floor columns in the presence of soft-storey mechanisms, leading to the partial of full collapse of the building structures*" (Zhao et al, 2009). As is known, soft storey action occurs due to interstorey stiffness difference caused by abrupt difference between storey height or unequal degradation of infill walls. That is why this irregularity is frequently encountered in mixed buildings, while the ground floor is used for commercial purposes, the other storeys are used for residential purposes. Another instance that meets this definition from Arlekar et al (1997) is "*Open first storey is a typical feature in the modern multistorey constructions in urban India*". Another example can be given as; "*Soft first storey is a typical feature in the RC buildings in Kathmandu Valley because the first stories of the building have been often used as commercial areas, shops, or car parking*" (Sharma et al, 2016).

As for Türkiye, the field investigations of past earthquakes showed that there is numerous instances of soft storey action. For example, a field investigation study done by Aydıner et al (2023) after recent major Kahramanmaraş earthquakes. In the study, the observed soft storey buildings compared with pre-earthquake state of themselves and the disastrous effect of this irregularity can be seen. The damages caused by earthquake resulted in inelastic behavior of structures. That is why, investigation of soft storey irregularity not only for elastic but also for inelastic behavior of building has own importance.

In the literature, there are studies that examined the impact of soft storey irregularity on the structural behavior of buildings, in reference to code criteria. Yousef et al. (2010) performed nonlinear time history analyses on high

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rise ductile buildings composed of both normal and high strength concrete, and compared the results with those from the ELF method. The applicability of the ELF method to buildings with vertical irregularities (in terms of mass, setback, and soft storey) was evaluated. The reliability of soft storey criteria in different seismic codes was assessed. The codes included UBC-97 (IBC-2000), Eurocode 8 (EC-8), Egyptian Codes for Loads (ECL-08), and ESEE-88. It was found that UBC-97 was not suitable for structures with mass or setback irregularities but was sufficiently conservative for soft storey irregularities. ESEE-88 was observed to be generally less conservative than ECL-08. The results indicated that the limit values in UBC-97 and ECL-08 criteria were satisfactory and could be extended by approximately 10%.

Döndüren and Nakipoğlu (2018) interpreted the soft storey criteria and corresponding limit values from DBYBHY-2007 (Türkiye), IS 1893-1-2002 (India), ASCE-7-2002 (USA), and the Japanese seismic design codes based on dynamic analyses conducted in SAP2000. 11 amount of models with varying ground floor heights were analysed. Factors such as the stiffness irregularity coefficient η_{ki}, storey stiffness ratio (k_1/k_2), and R_s values are calculated and compared with the respective limit values in the codes. The results revealed the onset of soft storey behavior and highlighted that the Japanese seismic code provided more reliable and conservative assessments.

Khanal et al. (2019) investigated the effects of varying ground floor heights on 5 amounts of 3D, 5 storey frame models using both linear static and nonlinear time history analyses. The presence of a soft storey was evaluated based on Japanese, Türkiye, and IS seismic codes. It is noted that while the Japanese and Türkiye code evaluations varied with the analysis method, the IS code provided consistent assessments regardless of the method. The Japanese code was found to be more conservative. Moreover, the study emphasised that story drift alone should not be the sole criterion for evaluating structural safety, as many models satisfied the drift requirement despite the presence of soft storey irregularity.

Zavala et al. (2022) explored the effects of stiffness irregularity and P-Δ effects on building response using 9 models of a 20 storey structure: 4 with both geometric nonlinearity and stiffness irregularity, 4 with only stiffness irregularity, and one reference model. Stiffness irregularity was evaluated on each storey according to ASCE-41-13 and nonlinear static pushover analyses were conducted. Results indicated that P-Δ effects became more critical in the presence of storey stiffness irregularity at lower storeys, with reductions in structural stiffness up to 56.3%. Literature studies on buildings with soft storey irregularity predominantly focus on relative displacements, natural periods, member damages, code based irregularity checks, and the quantification of irregularity degrees.

In this study, the code-defined soft storey evaluation methods are examined for both linear and nonlinear case. The code-defined stiffness irregularity factors calculated for each pushover step and compared with each other along with the pushover curve. The magnification effect of nonlinear behavior on soft storey action in a negative way is made visible by drawing graphs. Finally, the graphs drawn were interpreted.

2. Methodology

The examined building is 4 storey 2 bay reinforced concrete frame system with slabs (Fig. 2a, b). While the first storey height is 4.5 m, the others are 2.6 m, and the bay spacing is 3 m. In most cases, this case corresponds architecturally mixed purpose building, while the ground storey is used for commercial purposes, the other storeys are used as residential. Column sizes are determined as 30x25, and beam sizes are 30x40. The columns are placed so that the structure is weaker in the direction of loading (i.e. x axis). There is no infill and shear wall in the structural system. The source of soft storey action stems from the abrupt difference in column length at ground and one upper storey. All structural modeling done in SAP2000 structural analysis software (SAP2000, 2021). The view of structural system and ELF (equivalent lateral force) method loadings are given in Fig. 1a, b and d.

According to Article 28 of the Planned Areas Zoning Regulation of Türkiye, maximum ground floor height is 4.5 m if there is no mezzanine and the ground floor is used for commercial purposes (PAİY, 2017). Also, the minimum internal height of the floor should be higher than 2.6 m (PAİY, 2017). The structural design parameters are given in Table 1.

Table 1. Structural properties of the investigated building

Column section (cm)	30x25	Ground storey height (m)	4.5	Confinement diameters (mm)	12d
Beam section (cm)	30x40	Residential storey heights (m)	2.6	Confinement spacings (cm)	10
Bay width (m)	3	Concrete type	C30	Stiffness modifier of beam	35%
Support Type	Fixed	Reinforcement type	S420	Stiffness modifier of column	70%
Amount of storey	4	Slab type	Shell Thin	Stiffness modifier of slab (bending and membrane)	25%
Amount of bay	2	Column longitudinal rebar diameter (mm)	14d	Beam longitudinal rebar diameter (mm)	12d

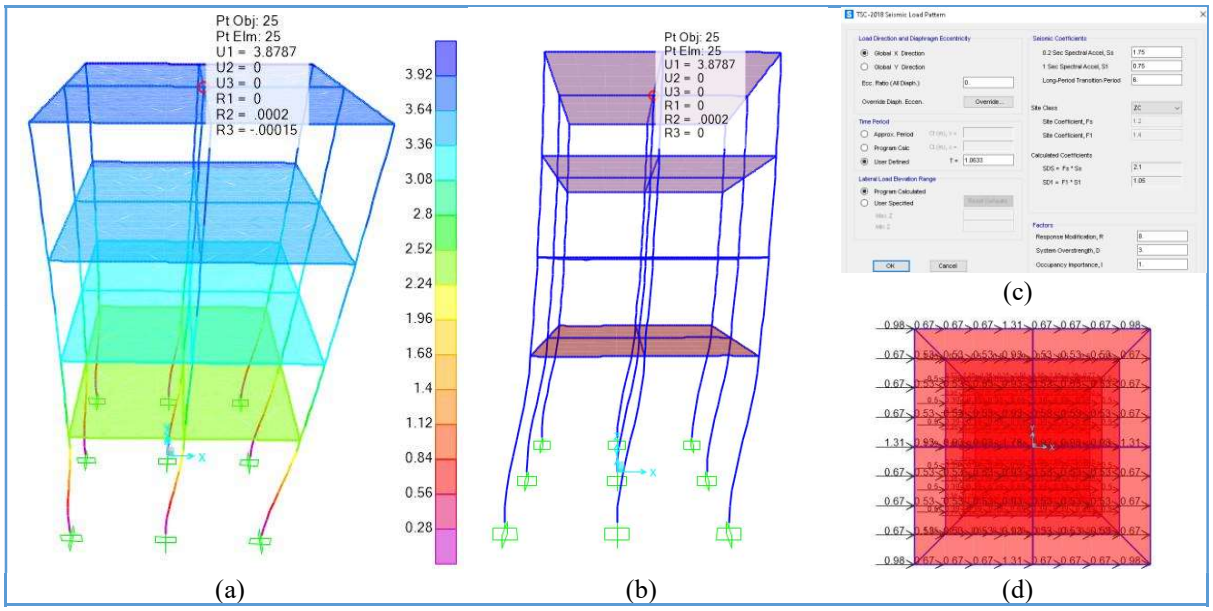


Fig. 1. SAP2000 Model of investigated structure of ELF method (a) displacement contour diagram of +5% eccentricity (b) displacement of zero eccentricity (c) Automatic TBDY-2018 quake loading (d) lateral loads distributed along floors

As indicated at the introduction, there are so many old building having soft ground storey in earthquake sites. As for old regulations like Specification for Structures to be Built in Disaster Areas 1997, size of 25x30 rectangular columns were permitted (ABYYHY, 1997). That was the minimum condition of column section sizes. In this study, the column size was selected in this opinion. For simplicity, all columns are placed at the same direction as the moment of inertia about y axis is weaker. The static loadings for both ELF and pushover acted on the weak direction of the structure, i.e. x direction at Fig. 1. The dead load is taken as $g = 1.5\ kN/m$, and so the live load $q = 2\ \ kN/m$. The mass source of the system is defined by $g + 0.3q$. The load bearing system is moment bearing reinforced concrete frame system which having high structural ductility. The system is assumed to satisfy the capacity and ductile design conditions. The slab thickness is taken as 12 cm and rigid diaphragm definition done at each storey level.

2.1. Soft storey irregularity criteria according to the different codes

In this paper, the soft storey action (i.e. interstorey stiffness irregularity) evaluated based on TBDY-2018 code, ASCE/SEI-7-10 code and BSL code. These codes defines a criterion and a limit value for checking whether the irregularity is valid or not. For Türkiye Building Earthquake Code (TBDY-2018), the criterion is based on whether the division of drift ratios of adjacent storeys is greater than 2. Thus, a stiffness irregularity factor is defined as (1).

$$\eta_{ki} = \frac{\frac{\Delta_i}{h_i}}{\frac{\Delta_{i+1}}{h_{i+1}}} > 2 \qquad (1)$$

Here Δ denotes storey drift, h denotes storey height, the subindex i denotes related storey number, the ratio of Δ_i / h_i denotes drift ratio of related storey, and η_{ki} denotes stiffness irregularity factor of related storey. If the inequality given in (1) is satisfied, that means the i th. storey is soft storey. As one can guess, if the ratio of drift ratios at (1) has been taken as upper storey divided by lower, then the inequality would change direction and the limit value would become 0.5.

The American Society of Civil Engineers ASCE/SEI-7-10 code criteria denotes the definition of a soft storey whose stiffness is less than 70% of the upper storey or 80% of the arithmetic mean of the three upper storeys. This criterion is the same one as UBC code. There is also definition of an extreme soft storey, which will be taken into account for this paper since the investigated structure already provides the extreme soft storey condition. The extreme soft storey condition clarified in the code given "*where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above*" (ASCE/SEI-7, 2010). The condition defined in the text can be defined in an inequality form as $k_i < 0{,}6k_{i+1}$ and $k_i < 0{,}8k_m$, where k_i corresponds to the related storey stiffness, k_{i+1} corresponds to one upper storey stiffness and k_m corresponds mean storey stiffness of three upper storey and defined at (4). As one can guess, if the lateral stiffness of lower storey divided by upper adjacent storey or the mean lateral stiffness of three upper storey divided by the lateral stiffness of related storey, the limit value would became as the inequality given at (2) and (3).

$$\frac{k_{i\pm1}}{k_i} > 1{,}67 \tag{2}$$

$$\frac{k_m}{k_i} > 1{,}25 \tag{3}$$

$$k_m = \frac{k_{i+1} + k_{i+2} + k_{i+3}}{3} \tag{4}$$

As for Building Standard Law of Japan (BSL), the irregularity is investigated by whether the ratio of reciprocal of drift ratio to average reciprocal of drift ratios of all storeys is less than 0.6. In that regard, a factor symbolized as R_s and defined in (5) is calculated.

$$R_{si} = \frac{r_{si}}{\overline{r_s}} < 0{,}6 \tag{5}$$

$$\overline{r_s} = \frac{\sum_{j=1}^{n} r_{sj}}{n} \tag{6}$$

Here while r_{si} is reciprocal of the drift ratio and calculated as h_i/Δ_i, $\overline{r_s}$ is average reciprocal of the drift ratio along all storeys (Aoyama, 1981). In (6), the amount of storey of building symbolized as n.

To sum up, the soft storey action is valif if the value of stiffness irregularity parameters or factors defined in the codes satisfies the corresponding criteria. The criteria defines limit values of those factors. The irregularity is valid if the irregularity factor η_{ki} to be greater than 2 as for TBDY-2018, or if the k_{i+1}/k_i is greater than 1.67 and k_m/k_i is greater than 1.25, or if the factor R_{si} is less than 0.6 limit value. Here one can see that while the inequality direction of TBDY-2018 criteria and ASCE/SEI-7-10 criteria is same, it is inverse for BSL code. In order for them to be compared meaningfully, the inequality direction of (5) changed by taking inverse of the multiplication of each part of the inequality. Thus, the limit value became 1 per 0.6.

$$R_{si}^{-1} = \frac{\overline{r_s}}{r_{si}} > \frac{1}{0.6} = 1.67 \tag{7}$$

As can be understood from the inequality (7), there is soft storey irregularity if R_{si}^{-1} term is greater than 1.67, and that also means R_{si} term to be lower than 0.6. As for calculations, the inequality of (7) will be taken into account. The summary of code-defined stiffness irregularity factor terms and their criteria with limit values that taken into account for this paper given in the Table 2.

Table 2. The conditions of existence of soft storey irregularity of a storey according to investigated codes

The related code	Factor	Definition	Criteria	Limit Value
TBDY-2018[*1]	η_{ki}	$\frac{\frac{\Delta_i}{h_i}}{\frac{\Delta_{i+1}}{h_{i+1}}}$	To Be Greater Than	2
ASCE-7-10[*2]	$\frac{k_{i+1}}{k_i}$	-	To Be Greater Than	1.67
	$\frac{k_m}{k_i}$	$\frac{k_{i+1} + k_{i+2} + k_{i+3}}{3k_i}$	To Be Greater Than	1.25
BSL[*3]	R_{si}^{-1}	$\frac{\overline{r_s}}{r_{si}}$	To Be Greater Than	1.67

[*1]TBDY-2018: Türkiye Building Eartquake Code - 2018
[*2]ASCE/SEI-7-10: American Society of Civil Engineers/Structural Engineering Istitute 2010
[*3]BSL: Building Standard Law of Japan

2.2. ELF analysis procedure

The linear elastic equilavent lateral force analysis done in order to determine the presence of soft storey irregularity. It is shown that the given structural design has soft story irregularity at the ground storey for all code criteria. The determination whether the irregularity is valid is done using TBDY-2018, ASCE/SEI-7-10 and BSL code criteria defined in (1), (2) and (3), (5) and (7) respectively. ELF procedure has been applied according to TBDY-2018 code. The load bearing system behavior factor is taken as $R = 8$. Site soil condition is taken as ZC. The soil magnification factors corresponding the ZC soil site condition is 1.2 for short period, and 1.4 for 1 second period. In terms of probabilistic seismic hazard assessment, the earthquake hazard level is taken as the earthquake having 2475 year recurrence period defined by TBDY-2018. While spectral acceleration for short period is taken $S_{ds} = 1.75\ g$, it is taken $S_{d1} = 0.75\ g$ as for 1 second period as can be seen from Fig. 1c. The deflected shape of structural system and top displacement can be seen from Fig. 1a, b. Lateral loading direction is taken as x axis and the distributed lateral loads along storey slabs can be seen from Fig. 1d. As can be seen from Fig. 1c, TBDY-2018 load pattern option at SAP2000 used for loading pattern. For both ELF and pushover method, the initial stiffness has been defined from $g + 0.3q$ loading. The calculated values of code-defined factors of ground storey according to linear elastic static analysis results given in the Table 3.

Table 3. The code-defined irregularity factors calculated from the ELF analysis results

$\Delta_1\ (mm)$	$\Delta_2\ (mm)$	$\Delta_3\ (mm)$	$\Delta_4\ (mm)$	$V_t\ (kN)$	$\Delta_1\ (kN)$
24.41	6.85	4.77	2.75	161.53	145.31
$V_3\ (kN)$	$V_4\ (kN)$	η_{k1}	k_2/k_1	k_m/k_1	R_{s1}^{-1}
115.04	72.30	2.059	3.206	3.607	2.786

Here in the Table 3; Δ_i corresponds relative storey drift, Δ_i corresponds storey shear, η_{k1} corresponds TBDY-2018 defined irregularity factor for ground storey, k_2/k_1. k_m/k_1 corresponds ASCE/SEI-7-10 defined criteria parameters for irregularity of ground storey and, R_{s1} is BSL defined factor calculated for ground storey. As for η_{k1}, the criterion is defined as (1), as for k_2/k_1 and k_m/k_1, the criterion is given at (2) and (3) respectively, and for R_{s1}^{-1}, the corresponding criterion is given in the inequality (7). These criteria are summarized at Table 2. One can see that the ground storey has stiffness irregularity for these three codes after comparing the irregularity factor results (Table 3), with their code-defined limit values (Table 2). Note that the storey shear of ground storey, V_1 corresponds to the base shear value.

2.3. Nonlinear static analysis procedure

As a nonlinear static analysis, displacement controlled nonlinear pushover analysis done up to the monitored top displacement of 24.6 cm, which corresponds to the 2% top drift ratio. The pushover load pattern is taken as the same one with equivalent lateral load pattern (Fig. 1.c) with zero eccentricity. The PΔ effects and large displacement taken into consideration, and the nonlinear static analysis began from the end of $g + 0.3q$ loading. The pushover curve is given in Fig. 2a.

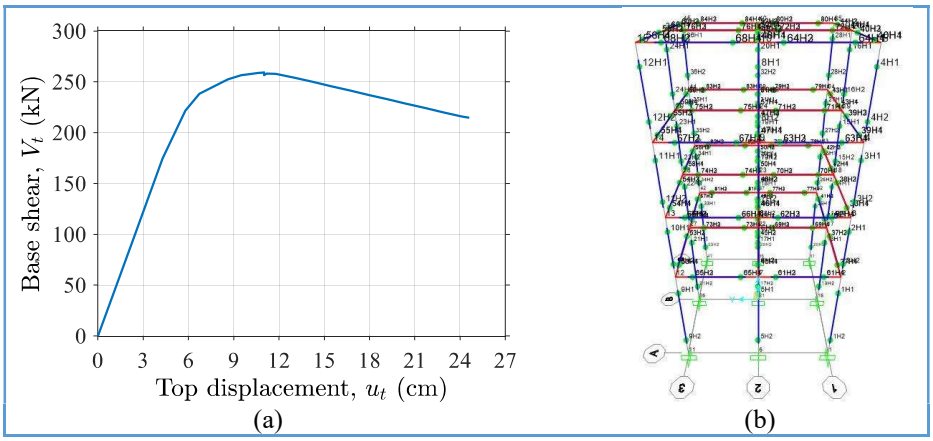


Fig. 2. Nonlinear static analysis case (a) Pushover curve of structure (b) assigned plastic auto hinges

The lumped plastic PMM hinges are defined using the idealised flexural hinge of the auto-hinge option of SAP2000. The assigned plastic hinges can be seen from Fig. 2b. The Plastic hinge length of the column has been calculated as half of the section width and assigned at the middle of the plastic hinge length. In that regard, while the plastic hinge length of columns is 15 cm, it is 20 cm for beams. Plastic hinge absolute distances are defined as 20 cm for columns and 25 cm for beams in x direction and 22.5 cm for beams in y direction, starting from the intersection point of the column and beam member axes.

3. Analysis results

In this paper, the values of code-defined stiffness irregularity factors through inelastic behavior of a reinforced soft storey structure are investigated and graphed along with incrementing top displacement. As can be understood from Table 2, relative storey drift values and storey stiffness values are needed to compute code-defined factors. The storey shear and drift values for all pushover steps are obtained from the SAP2000 analysis. The lateral storey stiffness, k_i calculated by dividing the storey shear, V_i into the relative storey drift, Δ_i. From the obtained results, values of code-defined factors are calculated for each pushover step. Nonlinear pushover analysis and irregularity factor results with the pushover step number given in the Table 4.

In Table 4, the values of irregularity factors are computed. They calculated using corresponding storey drifts and storey stiffnesses calculated from storey shear and storey drifts. The given analysis results are calculated only for the soft ground storey. In Table 4, step number corresponds the pushover step, u_{top} corresponds lateral top displacement for given pushover step, Δ_1, V_1 and Δ_2, V_1 corresponds storey drift and shear of ground and one above storeys and η_{k1}, k_2/k_1, k_m/k_1, R_{s1} are code-defined factors calculated for ground storey corresponding to given top displacement.

Table 4. The nonlinear pushover analysis results

Step No	u_{top} (cm)	Δ_1 (cm)	Δ_2 (cm)	V_1 (kN)	V_2 (kN)	η_{k1}	k_2/k_1	k_m/k_1	R_{s1}	R_{s1}^{-1}
1	1.23	0.77	0.22	50.02	45.08	2.06	3.21	3.63	0.359	2.79
2	2.46	1.55	0.43	100.13	90.19	2.06	3.21	3.62	0.359	2.79
3	3.69	2.32	0.65	150.32	135.33	2.06	3.21	3.62	0.359	2.79
4	4.29	2.70	0.76	174.76	157.34	2.06	3.21	3.62	0.359	2.79
5	5.80	3.66	1.08	221.71	199.75	1.97	3.06	3.74	0.346	2.89
6	6.73	4.34	1.24	238.27	215.01	2.02	3.16	4.04	0.321	3.11
7	8.61	5.87	1.51	252.53	228.84	2.25	3.52	4.95	0.264	3.78
8	9.52	6.67	1.60	256.58	231.51	2.41	3.77	5.46	0.239	4.18
9	10.02	7.14	1.63	257.39	232.25	2.54	3.96	5.80	0.226	4.43
10	10.17	7.27	1.64	257.99	232.78	2.57	4.01	5.89	0.222	4.49
11	10.63	7.69	1.66	258.70	233.41	2.67	4.17	6.19	0.212	4.72
12	10.96	8.00	1.68	259.20	233.86	2.74	4.28	6.40	0.205	4.87
13	11.02	8.04	1.69	259.34	234.61	2.75	4.30	6.43	0.205	4.89
14	11.02	8.08	1.66	256.42	231.29	2.81	4.38	6.49	0.202	4.94
17	11.19	8.22	1.68	258.13	232.62	2.83	4.42	6.55	0.200	5.00
18	11.80	8.82	1.70	257.92	232.85	3.00	4.69	7.01	0.188	5.32
19	13.03	10.08	1.68	254.13	229.48	3.46	5.40	8.11	0.163	6.12
20	14.26	11.34	1.67	249.84	225.73	3.93	6.14	9.27	0.144	6.96
21	15.49	12.61	1.65	245.59	222.10	4.40	6.89	10.45	0.128	7.81
22	16.72	13.87	1.64	241.35	218.47	4.89	7.66	11.68	0.115	8.69
23	17.95	15.13	1.63	237.11	214.83	5.38	8.44	12.94	0.104	9.60
24	19.18	16.40	1.61	232.87	211.20	5.88	9.23	14.23	0.095	10.54
25	20.41	17.66	1.60	228.63	207.57	6.39	10.04	15.58	0.087	11.50
26	21.64	18.92	1.58	224.40	203.94	6.91	10.87	16.96	0.080	12.50
27	22.87	20.19	1.57	220.16	200.30	7.44	11.72	18.39	0.074	13.53
28	24.10	21.45	1.55	215.93	196.67	7.98	12.58	19.87	0.069	14.59
29	24.60	21.96	1.55	214.54	194.94	8.21	12.91	20.45	0.066	15.05

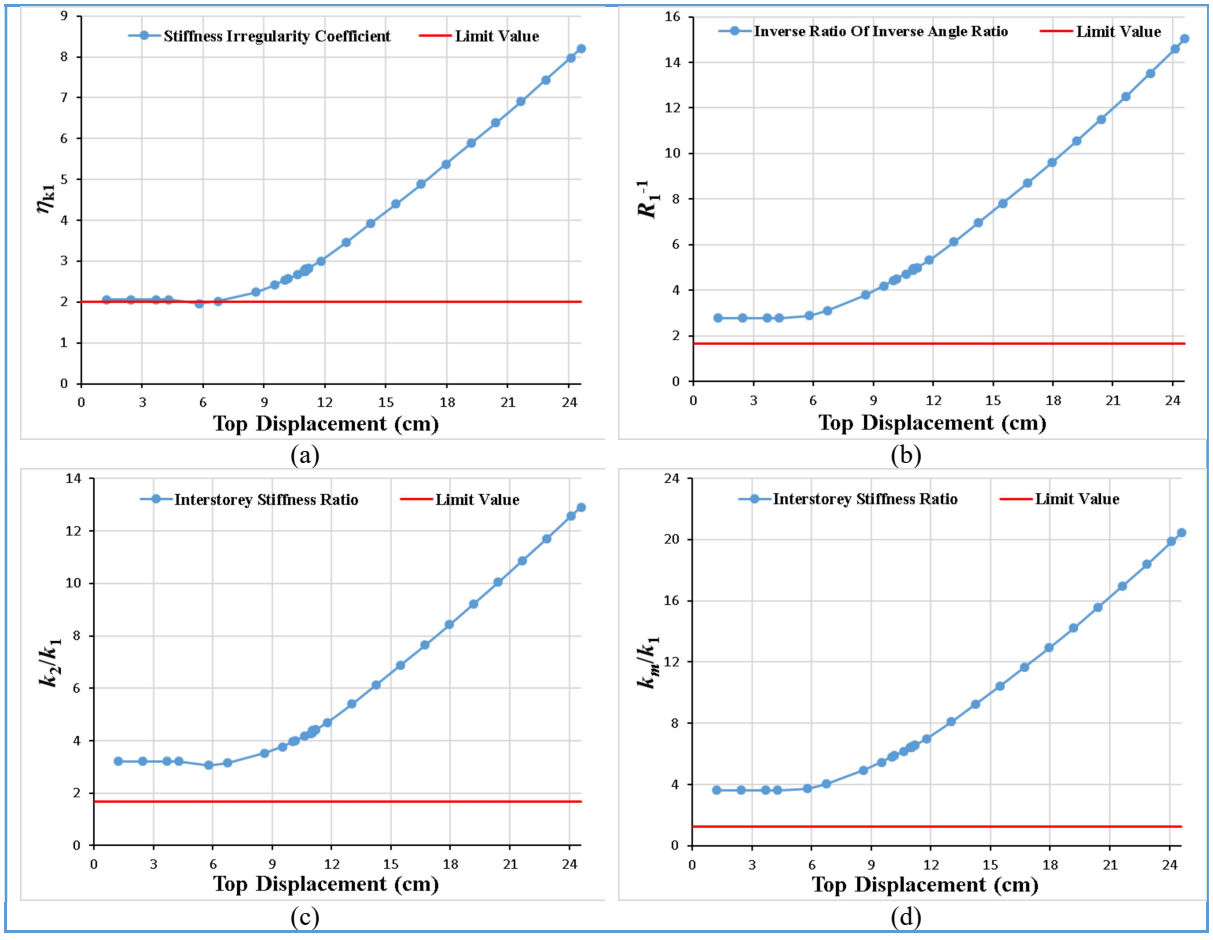


Fig. 3. Code-defined irregularity factor plots (a) TBDY-2018 (b) BSL (c) and (d) ASCE/SEI-7-10 codes

The pushover steps number 15 and 16 are repeated steps. That is why they were erased from Table 4. Storey shear is the sum of the shear force of the bottom section of columns at a storey, and the sum of the bottom section shear force of the ground storey corresponds to the base shear force. Storey stiffness, k_i obtained by the ratio of V_i to Δ_i. In order to observe the changing pattern of the factors of η_{k1}, k_2/k_1, k_m/k_1, R_{s1}^{-1} along with the inelastic behavior of the structure (Fig. 2a), the calculated values of factors are plotted according to the corresponding top displacement values obtained from SAP2000 and given in the Table 4. The plotted graphs are given in Fig. 3a, b, c and d.

In Fig. 3a, b, c and d, the red constant lines define corresponding code-defined limit values of criteria (1), (7), (2) and (3), respectively. The limit values for those inequality criteria are equal to 2 for Fig. 3a, 1.67 for Fig. 3b and Fig. 3c, and 1.25 for Fig. 3d. One can see that all irregularity factors tend to increase in the same manner, except slight decrease at 6 cm top displacement for Fig. 3a and Fig. 3c.

If one looks at all four graphs, one listed under the other, it can be understood that their patterns look identical. They become strictly increasing at the same top displacement, which is approximately 6 cm and corresponds to the governing of plastic hinges at columns. The structural stiffness is changing at the top displacement value approximately 6 cm and 11 cm drastically, as it can be seen from the pushover curve in Fig. 2. Both the slope of the elastic region and the post-strength slope is constant. In Fig. 3a, b, c and d, the corresponding slopes are nearly constant as well. While the increasing inelastic behavior of the structure, the irregularity factors also increased; on the other hand, if the structure remains elastic region, the irregularity factors remain unchanged. Also, it is seen that the pushover analysis results obtained when the frame behaves linearly elastic (the first four rows of Table 4), and the Table 3 results of irregularity factors obtained with the ELF method overlap with each other. This is valid until pushover step 5. This is not unpredictable since the pushover load pattern is taken as the same pattern defined at the ELF method and same stiffness modifiers are used. The first four pushover steps correspond to linear elastic analysis (until 4.3 cm top displacement) where no plastic hinge occurs. This can be seen from the pushover curve Fig. 2a as well.

Due to soft storey action, plastic hinges tend to occur at soft storey column ends before all beam end sections reach plastic moment capacity, resulting in less ductile behavior. But before reaching the ground storey mechanism, the governing of plastic hinges at ground storey beams could be the reason for the slight decrease in η_{k1} and k_2/k_1. The same slight decrease is not seen in Fig. 3b and d. Further investigation is needed to determine the exact reason.

The values of irregularity factors depend on the top displacement value for the inelastic region, and constant for elastic region of the building. That is why, instead of using the linear elastic ELF method to calculate irregularity factors and determine the presence of soft storey irregularity, the determination of soft storey can be evaluated for the top displacement of the inelastic displacement demand of the design earthquake as well.

4. Conclusions

Along with the nonlinear pushover analysis case, the inelastic behavior of the structure accounted for the calculation of each stiffness irregularity factor. Thus, the negative increase in soft story behavior is investigated for each code-defined criterion considered. From the analysis results and obtained graphs, the following can be said.

- The values of irregularity factors are constant for the elastic behavior of the structure. But if the structure crosses post-elastic region, the value of the irregularity factors increases with increasing top displacement for soft storey building. The considered codes have made a similar assessment in terms of the negative aggravation of the soft storey behavior throughout the inelastic behavior of the structure.
- The inequality direction of R_{s1} defined in the BSL code has been made the same inequality direction as TBDY-2018 and ASCE/SEI-7-10 criteria by taking into account of R_{s1}^{-1} using inequality (7) to be able to compare the code criteria in the same way. Thus, both elastic and inelastic behavior patterns of all four irregularity factors due to incrementing top displacement become similar.
- At 2% top drift ratio, the values of irregularity factors η_{k1}, k_2/k_1, k_m/k_1, R_{s1}^{-1} rose by 4, 4, 5.7 and 5.4 times respectively. The significant increase in code-defined stiffness irregularity factors begin by 6 cm top displacement where plastic hinges at ground storey columns occur and the factors increases up to 24.6 cm top displacement, which corresponds to 2% top drift ratio.
- The conservability of codes can be seen from how the elastic analysis results are far from the code-defined limit value. The ASCE/SEI-7-10 is the most conservative code, followed by the BSL code. As for investigated codes, the less conservative one is TBDY-2018. This result is consistent with literatüre review. Khanal et al (2019) was described Japanese code as more conservative than Türkiye code. Also Yousef et al (2020) denoted that UBC code is sufficiently conservative. This result is also consistent with the analysis done in this study since the ASCE and UBC criteria are same.

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