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Investigation of the effect of weak-story on earthquake behavior and rough construction costs of RC buildings

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Abstract. A significant portion of residential areas of Turkey is located in active earthquake zones. In Turkey occurred major earthquakes in last twenty years, such as Erzincan (1992), Kocaeli and Düzce (1999), Bingöl (2003), Van (2011). These earthquakes have demonstrated that reinforced concrete (RC) buildings having horizontal and vertical irregularities are significantly damaged, which in turn most of them are collapsed. Architectural design and arrangement of load-bearing system have important effect on RC building since architectural design criteria in design process provide opportunity to make this type of buildings safer and economical under earthquake loads. This study aims to investigate comparatively the effects of weak story irregularity on earthquake behavior and rough construction costs of RC buildings by considering different soil-conditions given in the Turkish Earthquake Code. With this aim, Sta4-CAD program based on matrix displacement method is utilized. Considering that different story height and compressive strength of concrete, and infill walls or their locations are the variables, a set of structural models are developed to determine the effect of them on earthquake behavior and rough construction costs of RC buildings. In conclusion, some recommendations and results related to making RC buildings safer and more economical are presented by comparing results obtained from structural analyses.

Keywords: construction cost; weak story irregularity; soft story irregularity; earthquake behavior

1. Introduction

Major earthquakes occur in relatively close period in Turkey located on active fault zone of the world and after earthquakes, majority of reinforced concrete (RC) buildings either have severe damage or are collapsed (Durmuş 1997, Scawthorn and Johnson 2000, Adalier and Aydingun 2001, Sezen *et al*. 2003, Spence *et al*. 2003, Doğangün 2004, Kaplan *et al*. 2004, Arslan and Korkmaz 2007, Celep *et al*. 2011, Ural 2013, Di Sarno *et al*. 2013). Detailed investigations on reasons for damages in structures have indicated that structural irregularities play critical role on earthquake behavior of RC buildings. Raising the awareness of complying with design rules for new

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structures has also considerable importance to make building safer and resistant to against earthquakes.

As in other countries, specifications for structures to be built in seismic zone are introduced in 2007 (TEC-2007) and since then this earthquake code has been used actively in Turkey. In this code, irregularities that cause damage to buildings are divided into two groups, which are irregularities in plan and in elevation. Irregularities in plan include torsional irregularity, floor discontinuities and projections in plan while irregularities in elevation are interstory strength irregularity (weak story), interstory stiffness irregularity (soft story) and discontinuity of vertical structural elements. Many earthquakes in Turkey, especially Kocaeli and Düzce (1999), Bingöl (2003) and Van (2011) earthquakes have shown that most of severe damages can result from the irregularities. On the other hand, majority of the irregularities in RC buildings take place at the beginning of architectural design level. Hence, architectural design rules are properly determined to reduce the existence of these irregularities. In addition, it is necessary for earthquake resistant design of buildings that different engineering and architectural disciplines should be in cooperation. The selection of the structural system of RC buildings affect significantly to the earthquake safety. Because of these reasons, architects are advised to in the design continuity, regular and symmetric structures (Dowrick 1987, Çatal and Ertutar 1990, Erman 2002, Celep 2004). Well arranged architectural designs are necessary certainly for withstanding destructive earthquake forces (Inan *et al*. 2012, Inan *et al*. 2014). Also, there are clear warnings and discouraging rules against these irregularities in the Turkey Earthquake Code (TEC-2007) due to the adverse effects in the response of buildings to earthquakes.

In this study, the effect of weak story irregularity called as B1 irregularity on earthquake behavior and rough construction costs of RC buildings is investigated comparatively by considering different soil classes given in the Turkish Earthquake Code (TEC). In addition, a set of structural models are developed to determine the effect of different story height and concrete class, and infill walls or their locations on earthquake behavior and rough construction costs of RC buildings. Thus, researchers and practitioners by examination of the findings obtained from the structural analyses are aimed to present of the results related to the RC buildings seismic performance and rough costs of the weak story irregularity.

2. B1-interstory strength irregularity (weak story)

There are diverse types of irregularities that should be avoided absolutely during the architectural design stage. Irregularities can be exist in the configuration of the building, differences between the story heights, in the distribution of masses and rigidities, in creating short columns, and in placement of the columns and shear walls (Gürsoy 2014). In this paper, only the weak-story irregularities are taken into account and structural analyses are carried out according to different soil classes given in the TEC.

Irregularities in arrangement of load-bearing system are caused significant damage to RC buildings. In other words, the discontinuities of load transfer of structural elements lead to damage and collapse. This results in loss of strength of these structural elements suddenly. That is to say, structural elements with discontinuities in load-bearing system have higher forces than those with continuity.

Ground story of buildings are usually used for commercial purpose, such as restaurant, shopping center, bank and car gallery. Therefore, especially infill walls are not considered this story to have large area here. However, the latest earthquakes occurred in Turkey have indicated that severe damages concentrated on ground story compared to the stories above. This is explained that ground story has much lower infill walls than the stories above (Tezcan *et al*. 2007, Kirac *et al*. 2011, Lee *et al*. 2011). This also means that displacement rigidity of ground story is lower than that of the other stories. Therefore, stories having especially fewer infill walls relative to the stories above are called as weak story.

2.1 Reasons for weak story irregularity

Weak story is defined as interstory strength irregularity in the TEC. The followings can be seen as the reasons for these irregularities

- Buildings with large span and window for commercial purpose, such as restaurant, hotel, shopping center, bank and car gallery,
- Omitting structural elements from building aimlessly,
- Buildings with ground story having fewer infill walls than the stories above,
- Reducing infill walls partially in ground story for certain purposes,
- Minimizing cross-sectional dimensions of column and shear wall to have large area,
- Reducing the number of columns and shear walls to add interstory to be used for conference hall and restaurant etc. in hotel and work center.

Structural measures to prevent for weak story irregularities are to model of building as pyramid form instead of half story form, to use stirrup along height of columns of possible weak story, to increase sectional dimensions of columns of especially ground story and to consider diagonal bracing elements. In addition, it is very important for earthquake behavior of RC buildings to use construction material with same specifications in all stories.

2.2 Criteria of weak story irregularity according to TEC-2007

Weak story is one of the irregularities in plan and called as B1 in TEC. In TEC, this irregularity is defined that lateral load capacity of i^{th} story is lower than that of $(i-1)^{th}$ or $(i+1)^{th}$ story which is neighbor on i^{th} story. Whether weak story irregularity is available for a building or not is determined by strength irregularity factor (η_{ci}) which is defined as the ratio of the effective shear area of any story to that of the story immediately above. This ratio is less than 0.8 as in Eq. (1) below

$$(\eta_{ci})_{min}=(\sum A_e)_i \,/\, (\sum A_e)_{i+1}<0.80 \tag{1}$$

where, $\sum A_e$ is the total infill walls area. Total infill area is calculated by Eq. (2) given below

$$\sum A_e=\sum A_w+\sum A_g+0.15\sum A_k \tag{2}$$

where,

$\sum A_w$: Sum of effective web areas of column cross sections, A_w's at any story

$\sum A_g$: Sum of section areas of structural elements at any story behaving as structural walls in the direction parallel to the earthquake direction considered

$\sum A_k$: Sum of masonry infill wall areas (excluding door and window openings) at any story in the direction parallel to the earthquake direction considered

Weak story irregularity (B1) of RC buildings is controlled in TEC as shown in Fig. 1. Here, it should be noted that considerations below are repeated for each of the orthogonal directions, x and y direction and all calculations are made by taking into account minimum (η_{ci}).

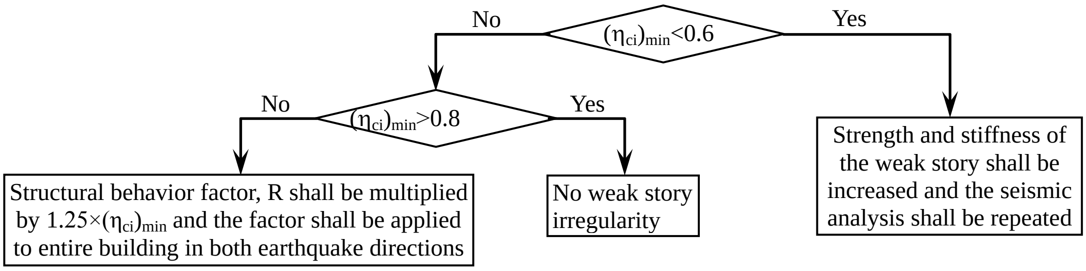

Fig. 1 Flowchart of weak story irregularity of RC buildings

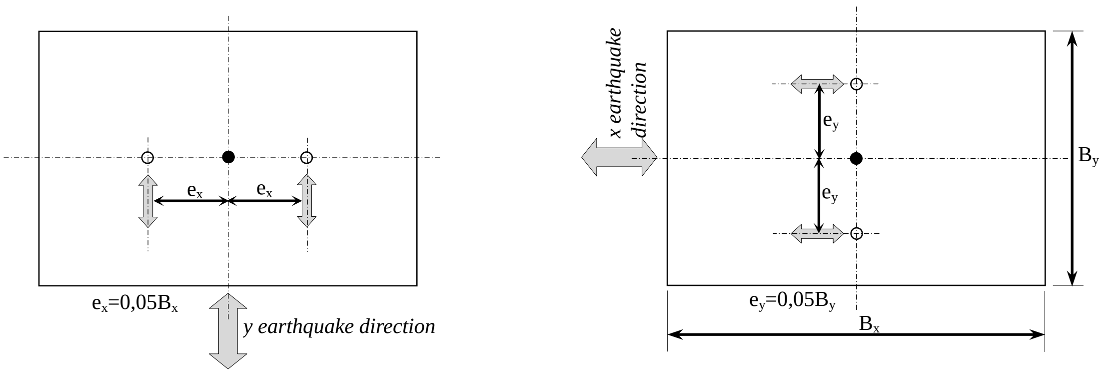

Fig. 2 Application of ±5% additional eccentricity of earthquake forces (TEC 2007)

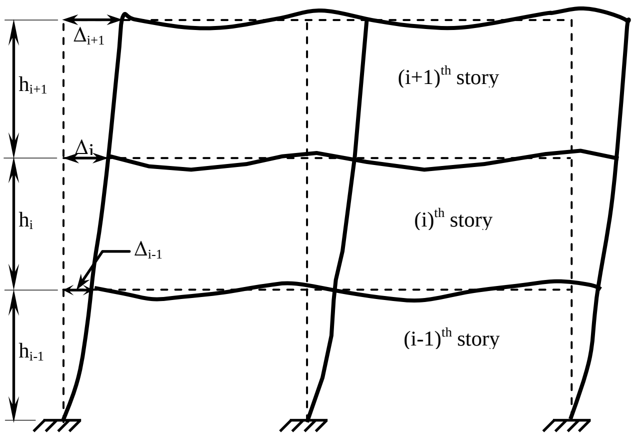

Fig. 3 Control of soft story irregularity of RC buildings

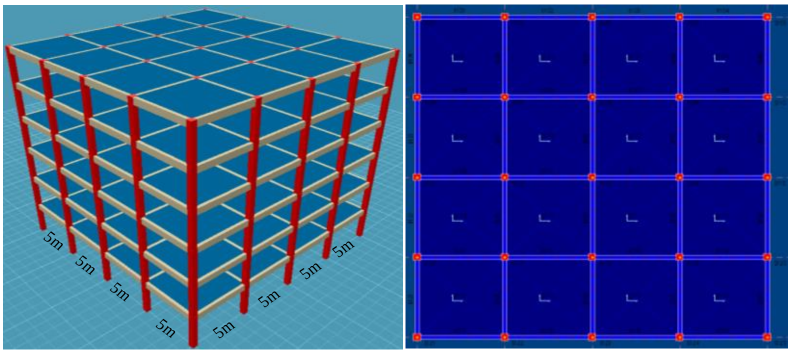

Fig. 4 Views of six-story (ground floor +5 typical floor) of the model considered in this study

3. B2-interstory soft story (stiffness) irregularity and soft story criteria according to TEC

Another irregularity in elevation is interstory stiffness irregularity called as soft story. This irregularity takes place where stiffness of any story decreases suddenly relative to the story above. TEC defines this irregularity as the ratio of the average story drift at any story to the average story drift at the story immediately above. Considering the effects of ±5% additional eccentricities, this ratio called as stiffness irregularity factor (η_{ki}) is calculated by Eq. (3) for each of both earthquake directions. Here, the displacement computations on both earthquake directions are considered the ±5% additional eccentricity (Fig. 2). As it can be seen from Eq. (3), in case of soft story irregularity, η_{ki} is greater than 2.

$$\eta_{ki} = \frac{(\Delta_i / h_i)_{ort}}{(\Delta_{i+1} / h_{i+1})_{ort}} > 2 \qquad \text{or} \qquad \eta_{ki} = \frac{(\Delta_i / h_i)_{ort}}{(\Delta_{i-1} / h_{i-1})_{ort}} > 2 \tag{3}$$

where,
Δ_i:Story drift of ith story of building (Δ_i=d_i-d_{i-1})
h_i:Height of ith story of building

In the TEC, whether soft story is available for any building is controlled according to Eqs. (4) and (5) as in Fig. 3.

$$\frac{R.(\Delta_i)_{\max}}{h_i} \le 0.02 \tag{4}$$

and

$$\theta_i = \frac{(\Delta_i)_{ort}.\sum_{j=1}^{N} w_j}{V_i.h_i} \le 0.12 \tag{5}$$

where,
N:Total number of stories of building from the foundation level

R:Structural behavior factor (ductility coefficient)
V_i:Story shear at i^{th} story of building in the earthquake direction considered
$(\Delta_i)_{ort}$:Average story drift of i^{th} story of building
θ_i:Second order effect indicator defined at i^{th} story of building

Structural measures to prevent for soft story irregularity are to provide uniformity for vertical structural elements, infill walls and height of each story of RC building, to increase sectional dimensions of structural elements or to use lateral stirrup along the height of columns and shear walls in possible soft story.

4. Numerical example

In this study is aimed the evaluation of effect of the soft story and weak story irregularities defined in the TEC in determining cost and earthquake behavior of RC buildings with the same floor gross area. For numerical example, nine RC buildings with six stories and four spans in both directions in plane are developed (Öz 2014). The stiffness distribution in both directions the selected models to avoid the additional internal forces due to structural torsional are taken symmetrically and mass center with rigid center are coincident in all models. General features of structural models are summarized below

- In model-1, all stories have same height of 3 m and structural irregularity isn't available.
- In model-2, ground story and the other stories have height of 5 m and 3 m, respectively.
- In model-3, the height of story are considered as 4 m, no infill walls at internal part of building, no mid-column and infill walls with height of 1.5 m at the edge of building for 5^{th} story, and height of 3 m for the others story are considered.
- In model-4, 1^{st} story and the other stories have height of 5 m and 3m, respectively.

Table 1 The soil types properties defined in TEC

Soil type	The soil topmost layer thickness (h_1)	Description of Soil types
Z1	-	Massive volcanic rocks, unweathered sound metamorphic rocks, stiff cemented sedimentary rocks V_s>1000 m/s; very dense sand, gravel V_s>700 m/s; hard clay, silty lay V_s>700 m/s
	$h_1 \leq 15$ m	Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity $V_s \approx 700$-1000 m/s; dense sand, gravel $V_s \approx 400$-700 m/s; very stiff clay, silty clay $V_s \approx 300$-700 m/s
Z2	$h_1 > 15$ m	Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity $V_s \approx 700$-1000 m/s; dense sand, gravel $V_s \approx 400$-700 m/s; very stiff clay, silty clay $V_s \approx 300$-700 m/s
	$h_1 \leq 15$ m	Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity $V_s \approx 400$-700 m/s; medium dense sand and gravel $V_s \approx 200$-400 m/s; stiff clay and silty clay $V_s \approx 200$-300 m/s
Z3	15 m$<h_1 \leq 50$ m	Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity $V_s \approx 400$-700 m/s; medium dense sand and gravel $V_s \approx 200$-400 m/s; stiff clay, silty clay $V_s \approx 200$-300 m/s
	$h_1 \leq 10$ m	Soft, deep alluvial layers with high water table V_s<200 m/s; loose sand V_s<200 m/s; soft clay, silty clay V_s<200 m/s

Table 2 Project parameters of the structural models considered in this study

Earthquake zone		1
Effective ground acceleration coefficient (A_0)		0.4
Building importance factor (I)		1
The structural behaviour factor (R)		4
Live load (kN/m^2)		2
Live load factor		0.3
Bedding values of the foundation soils (kN/m^3)	for Z1 soil class	200000
	for Z2 soil class	100000
	for Z3 soil class	30000
Allowable bearing values of the foundation soils (kN/m^2)	for Z1 soil class	1000
	for Z2 soil class	500
	for Z3 soil class	200
Design spectrum characteristic periods (s)	for Z1 soil class	T_A=0.10 / T_B=0.30
	for Z2 soil class	T_A=0.15 / T_B=0.40
	for Z3 soil class	T_A=0.15 / T_B=0.60
Concrete class (C)		C30
		C20
Concrete young's modulus (N/mm^2)	for C30	32000
	for C20	28000
Concrete compressive strength, f_c (N/mm^2)	for C30	30
	for C20	20
Tensile strength of concrete, f_t (N/mm^2)	for C30	1.9
	for C20	1.6
Steel class (S)		S420
		S220
Steel young's modulus (N/mm^2)		200000
Yield stress of steel, f_y (N/mm^2)	for S420	420
	for S220	220
Slab thickness (m)		0.15
The cross-sectional dimensions of beam (cm)		25x50
The cross-sectional dimensions of column (cm)		40x40
Thicknesses of the infill brick wall (cm)		19
Infill brick wall young's modulus (MPa)		1000

- In model-5, ground story has height of 5 m and half story with height of 3 m in 2 span.
- In model-6, ground story has height of 5 m and half story with height of 3 m in 1 span.
- In model-7, all stories have height of 3 m, 20 MPa concrete strength and 220 MPa yield of steel reinforcement bars at the 1st story, and 30 MPa concrete strength and 420 MPa yield of steel reinforcement bars at the other stories are considered.

- In model-8, all stories have height of 3 m, 20 MPa concrete strength and 420 MPa yield of steel reinforcement bars at the 1st story, and 30 MPa concrete strength and 420 MPa yield of steel reinforcement bars at the other stories are considered.
- In model-9, all stories have height of 3m, 30 MPa concrete strength and 220 MPa yield of steel reinforcement bars at the 1st story, and 30 MPa concrete strength and 420 MPa yield of steel reinforcement bars at the other stories are considered.

The reference model (model 1) shown in Fig. 4 is considered for numerical application. All models are designed to have same story gross area (400 m^2). According to the building code requirements for reinforced concrete (TS500, 2000), except for model-7, model-8 and model-9, the rest of them are developed by considering 30 MPa concrete strength and 420 MPa yield of steel reinforcement bars. In all models, beams and columns have same sectional dimensions. The thickness of slabs is selected as 15 cm for all stories in each model. In addition, all models are assumed to be in the 1st degree earthquake zone according to TEC. Therefore the effective ground acceleration coefficient is taken 0.4. Also, the properties of different soil types defined in the TEC given in Table 1. As seen from Table 1, information about different soil types given in the TEC depend on the topmost layer thickness of soil (h_1). Other parameters considered in structural analysis are summarized in Table 2.

In this study, the effect of rough construction cost of weak story irregularities is comparatively examined with help of Sta4-CAD program (Sta4-CAD 2010) which uses the matrix displacement method. This examination is done with frameworks which have different weak story coefficients according to proposed design spectrum for soil classes given in the TEC. The necessary controls in the analyses are made in accordance with the current TEC and TS500.

5. Findings and discussions

The aim of this study is to investigate the effects on the earthquake behavior and the rough construction quantities of RC buildings which have different weak story irregularities. The considered models are designed as frame systems.

Insufficient structural elements under earthquake loads are shown in Figs. 5-13, respectively. These results are obtained from different soil classes given in the TEC by using Sta4-CAD program.

The results obtained from the structural analyses can be summarized as;

- In model-1; sectional dimensions of some columns and beams are inadequate for Z3 soil class as shown in Fig. 5.
- In model-2; sectional dimensions of all columns and some beams of ground story for Z1 and Z2 soil classes, and sectional dimensions of columns and beams of ground story and some beams of 1st story for Z3 soil class are inadequate as shown in Fig. 6.
- In model-3; sectional dimensions of some beams of the top floor for Z1 and Z2 soil classes, and sectional dimensions of some columns and beams of ground and 1st stories for Z3 soil class are inadequate as shown in Fig. 7.
- In model-4; sectional dimensions of some columns of 1st story for Z1 soil class, sectional dimensions of all columns and some beams of 1st story and some beams of ground story for Z2 soil class, and sectional dimensions of some columns and all beams of ground story and all columns and beams of 1st story for Z3 soil class are inadequate as shown in Fig. 8.

- In model-5; sectional dimensions of all columns and some beams of ground story for Z1 and Z2 soil classes, and sectional dimensions of all columns and some beams of ground story and some beams of 1st story for Z3 soil class are inadequate as shown in Fig. 9.
- In model-6; sectional dimensions of all columns and some beams of ground story for Z1 and Z2 soil classes, and sectional dimensions of all columns of ground story and some beams of ground and 1st stories for Z3 soil class are inadequate as shown in Fig. 10.
- In model-7; sectional dimensions of all beams and some columns of 1st story for Z1 and Z2 soil classes, sectional dimensions of some beams of 2nd story, some columns and all beams of 1st story and some columns and beams of ground story for Z3 soil class are inadequate as shown in Fig. 11.
- In model-8; sectional dimensions of some columns of 1st story for Z1 and Z2 soil classes, and sectional dimensions of some columns and beams of ground and 1st stories and some beams of 2nd story for Z3 class are inadequate as shown in Fig. 12.
- In model-9; sectional dimensions of all beams of 1st story for Z1 and Z2 soil classes, and sectional dimensions of some columns and beams of ground story, all beams and some columns of 1st story and some beams of 2nd story for Z3 soil class are inadequate as shown in Fig. 13.

These results have shown that behavior of model-1 (the reference model) not having weak story irregularity under earthquake loads is better than that of the other models considered in the study. In other words, the structural analyses demonstrate that the model-1 is very well behaved.

According to soil classes defined in the TEC, distributions of total reinforcement steel and concrete quantities of the models are shown in Figs. 14 and 15, respectively. As shown in Fig. 14, minimum total reinforcement steel quantity is obtained from model-1. Besides, steel quantities increases from Z1 to Z3. This conclusion has shown that model-1 with no weak story irregularity is more economical than the other models. Similarly, minimum total concrete quantity is calculated in model-1 (the reference model). As shown in Fig. 15, it also observed that variation of concrete quantity from Z1 to Z3 is constant. These finding reveal that the weak story irregularity in terms of cost in design of RC buildings is important, too.

Here, it should be noted that the sectional dimensions in the other models (except model-1) will be increased to ensure adequate safety in the structural systems, total reinforcement steel and concrete quantities of the model with increased sectional dimensions are greater than that of initial models those shown in Figs. 14 and 15.

Maximum expected lateral force (base shear) and 1st fundamental vibration period obtained from structural analyses of the models for soil classes proposed in the TEC are given in Table 3. From this table, fundamental vibration period of the models having weak story irregularity is to be higher than that of model-1 which not having this irregularity. In addition, base shear forces of all models in this study increase from Z1 to Z3. Base shear forces of model-1 not having weak story irregularity have greater than that of the other models. This result has shown that weak story irregularity decreases base shear capacity of building. In other words, this irregularity causes poor behavior of RC building under earthquake loads. Therefore, soil class and weak story irregularity can be seen as significant parameters for earthquake behavior of RC building.

Distributions of story displacement of the models in x and y directions for soil classes proposed in the TEC are given in Figs. 16-21, respectively. As seen from these figures, story displacements of model-1 in both directions are lower than those of other models. These values of the models with weak story irregularity increase suddenly. These findings have revealed that earthquake behavior of model-1 is better than that of the other models.

Control of weak story irregularity obtained from structural analyses conducted with Sta4 CAD programs of considered models in this study is given in Table 4. From this table, all models except for model-1 have weak story irregularity. As in Table 4, comparative control of soft story irregularity of considered models in this study is given in Table 5. Both weak story and soft story irregularity are seen in model-2 and model 4-6 for Z3 soil class.

Here, it should be noted that not be seen in this table of weak story irregularities seen in model-7, model-8 and model-9 (see Figs. 11-13, respectively) be due to take no account of concrete class in relation proposed in the TEC in force today.

In order to remove to weak story irregularity by increasing the concrete class for Z1 soil class of considered models in this study, required minimum concrete class and associated 1st fundamental vibration period are given in Table 6. From this table, it is seen that the weak story irregularity by increasing the concrete class can be removed. This matter shows that the effect on weak story irregularity of the material strength. In other words, it is seen that the concrete strength is very important parameter on weak story irregularity. The models having increased concrete strength have lower 1st fundamental vibration period than the other models with weak story irregularity. This finding has shown the extremely importance of concrete strength.

Here, it should be noted that targeted the elimination of weak story irregularity by increasing only the concrete class according to TEC in this day force. Because the S220 steel class isn't used in Turkey today. Therefore, results from model 7-9 are not given in this table since they have the irregularity resulting from reinforcement steel class.

Total reinforcement steel quantity of the initial models and the models having increased concrete class for Z1 soil class are given in Fig. 22. From this figure, model-1 that doesn't weak story irregularity has minimum reinforcement steel quantity. It is also observed that reinforcement steel quantity of the models having increased concrete class decreases compared to that of the initial models. This finding reveals that concrete class is very important parameters for weak story irregularity and rough cost of RC building.

Here, it should be noted that only Z1 soil class is considered since concrete strength increases up to 100 MPa from Z1 to Z3.

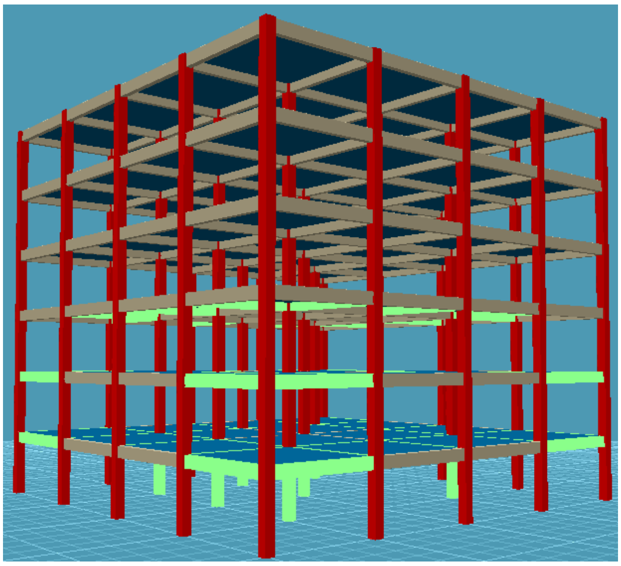

Fig. 5 View of inadequate structural elements of model-1 for Z3 soil class

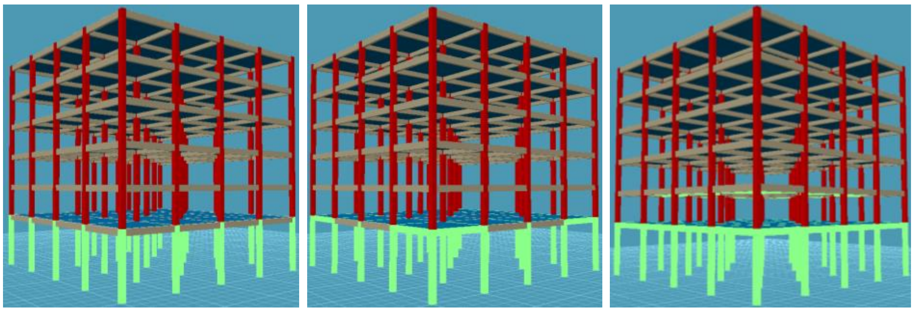

Fig. 6 View of inadequate structural elements of model-2 for Z1, Z2 and Z3 soil classes

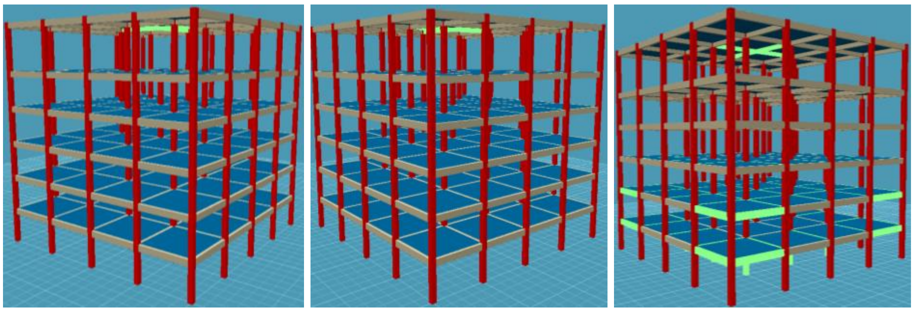

Fig. 7 View of inadequate structural elements of model-3 for Z1, Z2 and Z3 soil classes

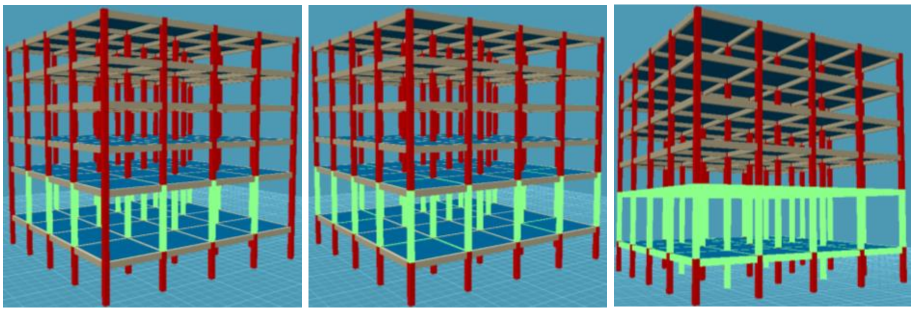

Fig. 8 View of inadequate structural elements of model-4 for Z1, Z2 and Z3 soil classes

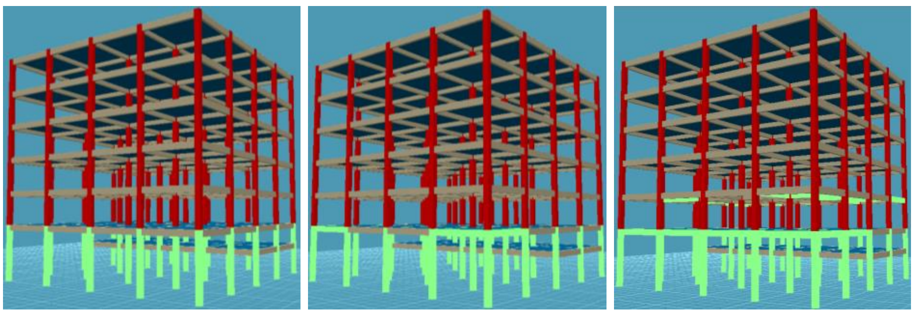

Fig. 9 View of inadequate structural elements of model-5 for Z1, Z2 and Z3 soil classes

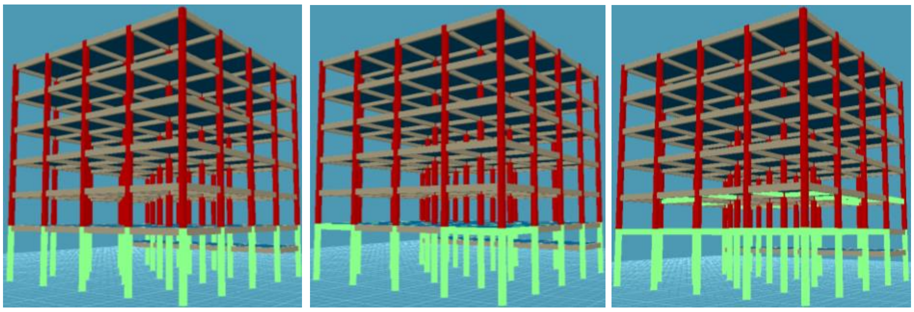

Fig. 10 View of inadequate structural elements of model-6 for Z1, Z2 and Z3 soil classes

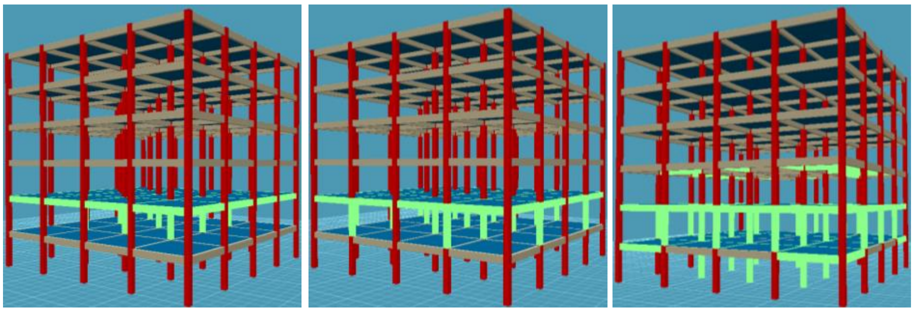

Fig. 11 View of inadequate structural elements of model-7 for Z1, Z2 and Z3 soil classes

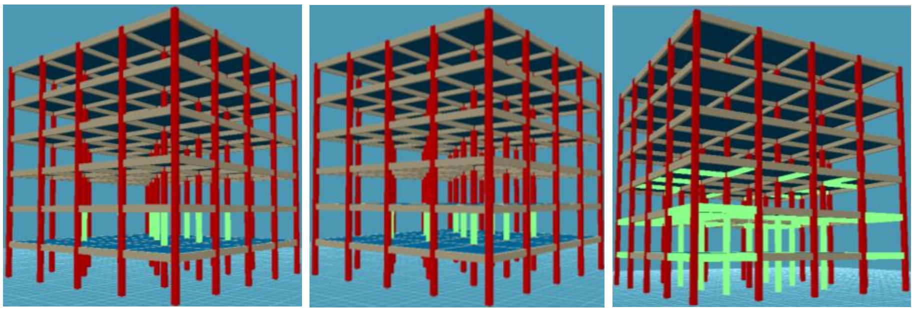

Fig. 12 View of inadequate structural elements of model-8 for Z1, Z2 and Z3 soil classes

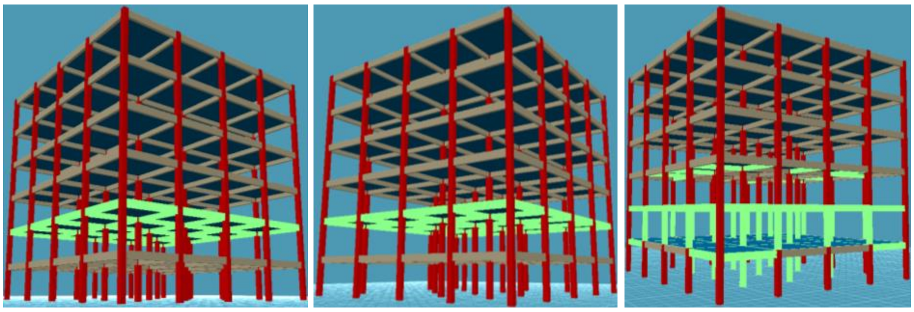

Fig. 13 View of inadequate structural elements of model-9 for Z1, Z2 and Z3 soil classes

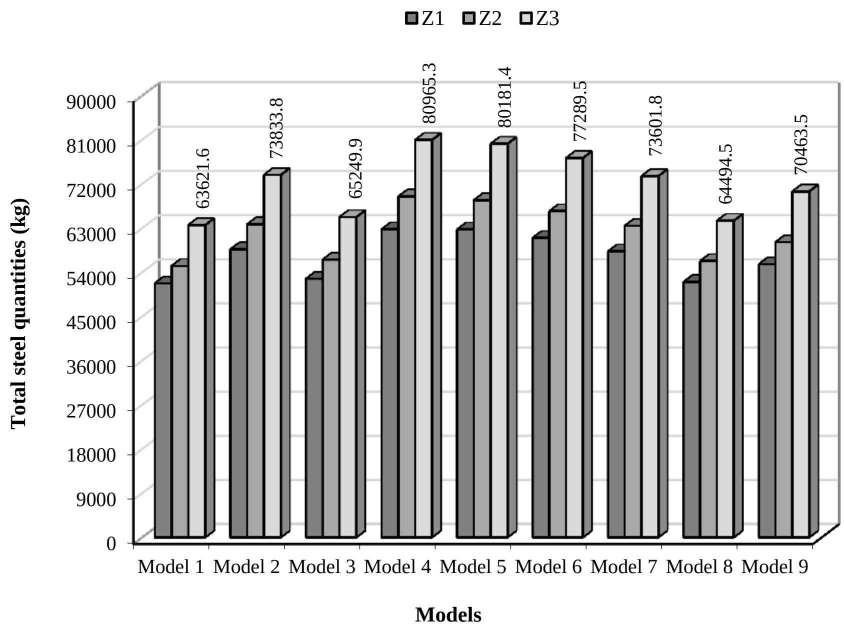

Fig. 14 Distribution of total reinforcement steel quantity according to Z1, Z2 and Z3 soil classes

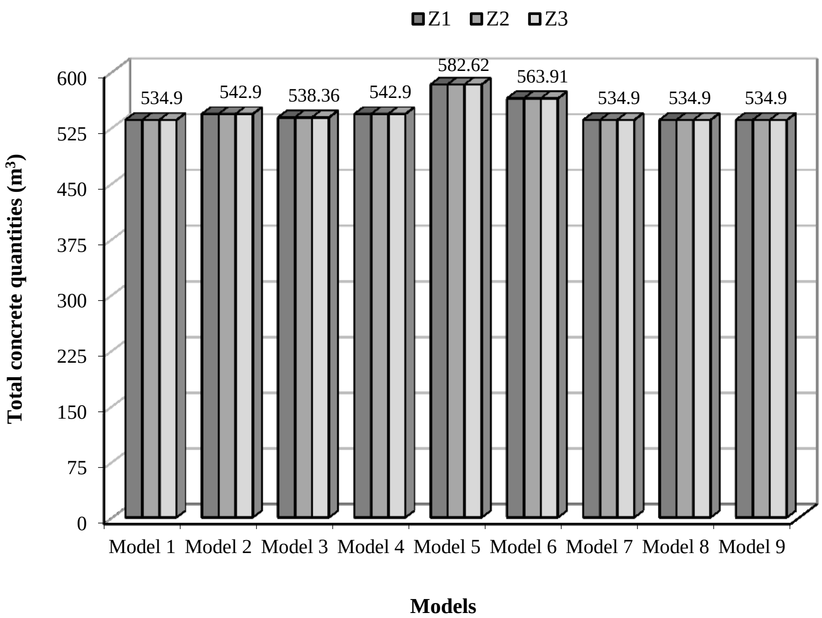

Fig. 15 Distribution of total concrete quantity according to Z1, Z2 and Z3 soil classes

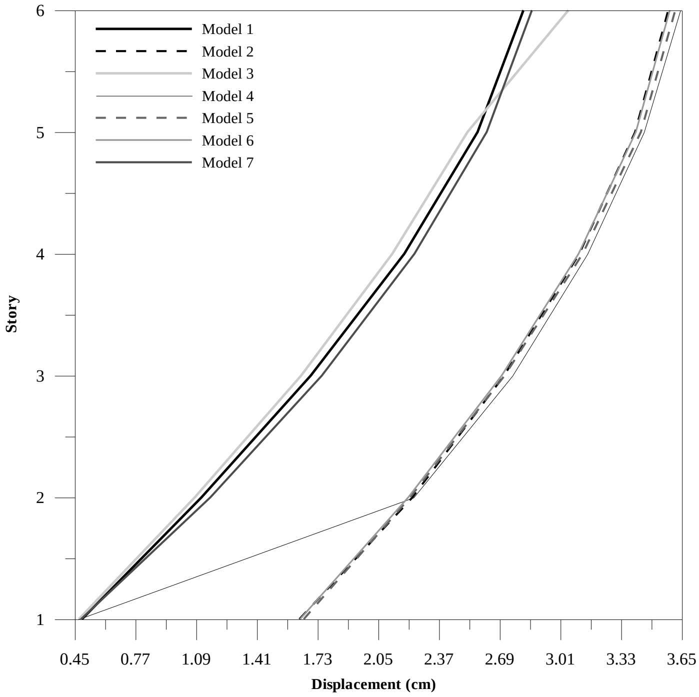

Fig. 16 Story displacement of the models in x direction for Z1-soil class

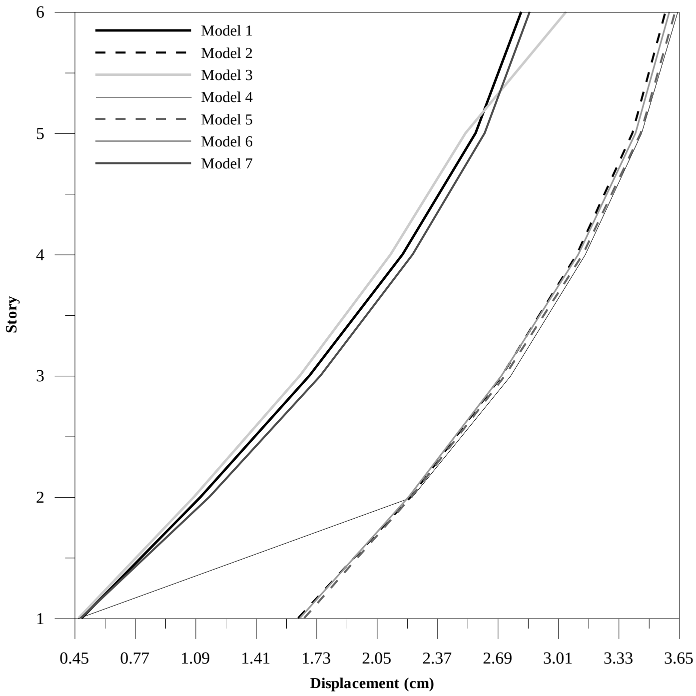

Fig. 17 Story displacement of the models in y direction for Z1-soil class

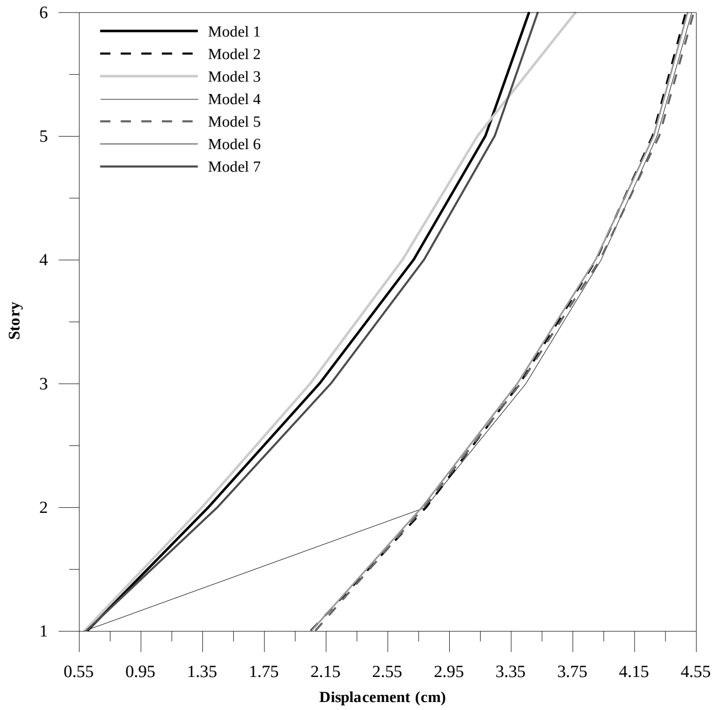

Fig. 18 Story displacement of the models in x direction for Z2-soil class

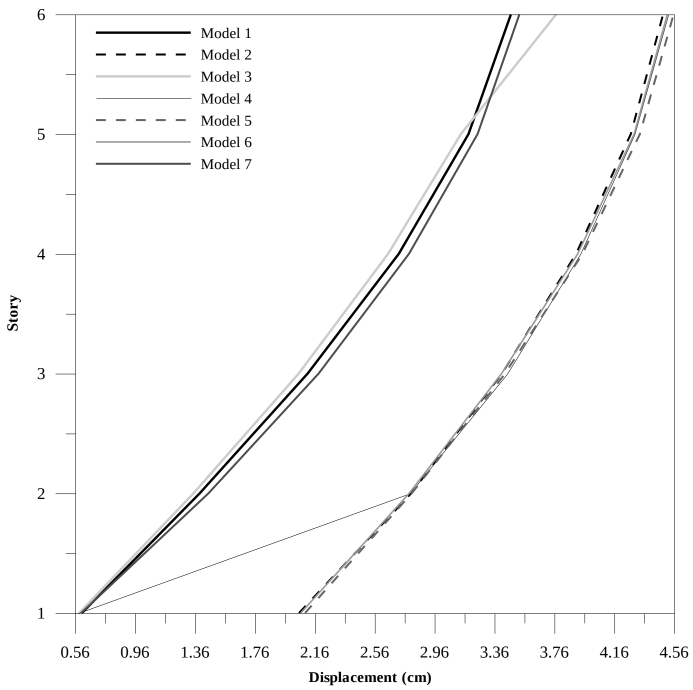

Fig. 19 Story displacement of the models in y direction for Z2-soil class

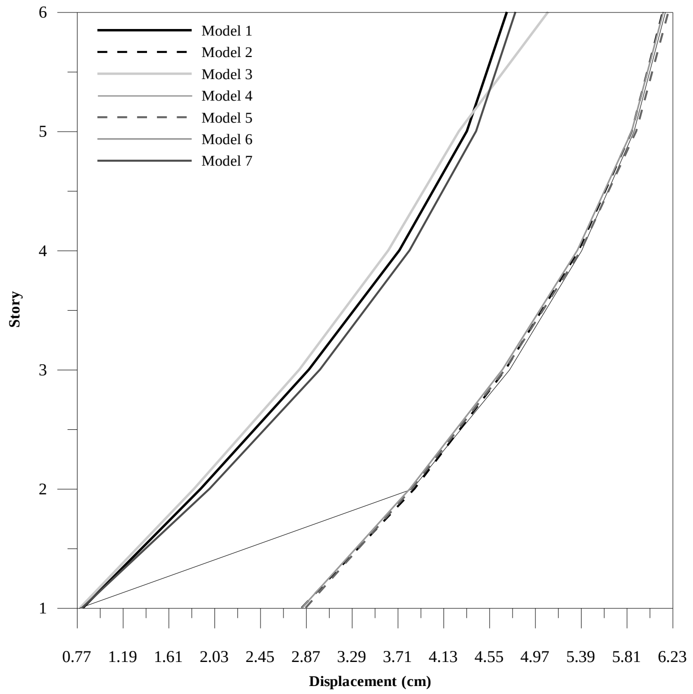

Fig. 20 Story displacement of the models in x direction for Z3-soil class

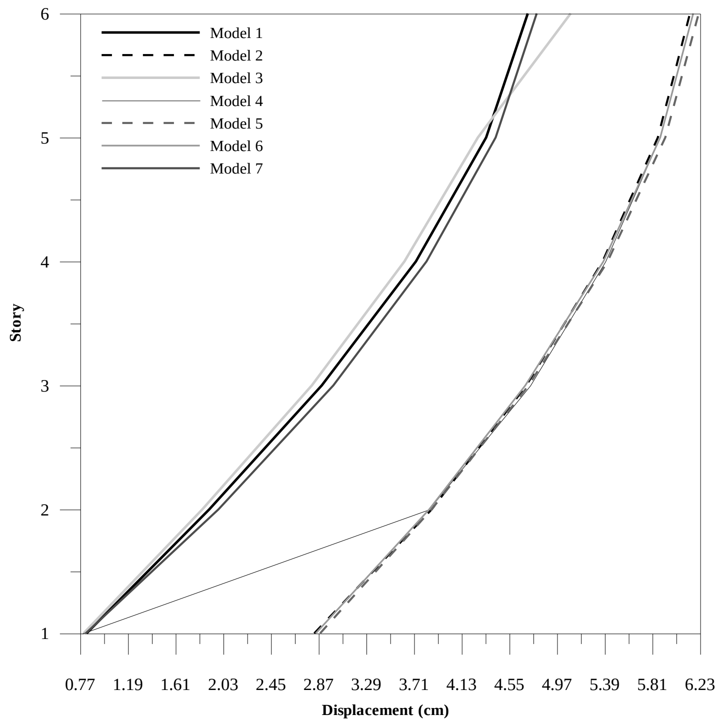

Fig. 21 Story displacement of the models in y direction for Z3-soil class

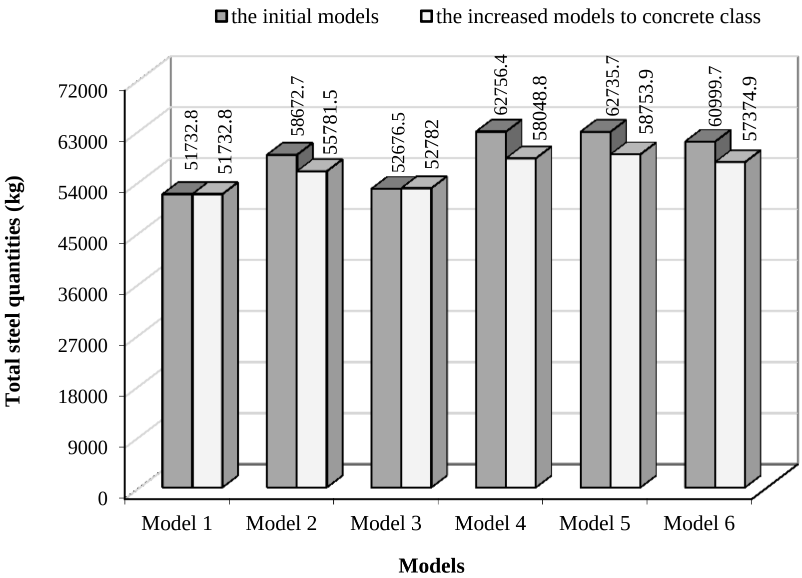

Fig. 22 Variation of total reinforcement steel quantity for Z1-soil class.

Table 3 1st fundamental period and base shear of the models

Models	Base Shear (kN)			Period (T_1)
	Z1	Z2	Z3	
Model 1	303.08	381.51	527.69	0.90
Model 2	245.38	308.88	427.24	1.18
Model 3	298.16	375.31	519.12	0.92
Model 4	252.91	318.36	440.34	1.19
Model 5	267.88	337.20	466.40	1.17
Model 6	258.16	324.97	449.49	1.17
Model 7	298.71	376.01	520.08	0.92
Model 8	298.71	376.01	520.08	0.92
Model 9	303.08	381.51	527.69	0.90

6. Conclusions

The purpose of this study is to examine the effects on rough construction costs and earthquake behaviors of reinforced concrete buildings of different weak story irregularities. Thus the results obtained from other models with reference model (model 1) are to compare. These comparisons are made based on concrete quantities, displacements and steel quantities by considering different soil classes given in the TEC. The main conclusions and recommendations obtained from this study are given below

- According to soil classes given in TEC, model-1 has minimum total reinforcement steel quantity. This finding has shown that model-1 is more economical than the other models. In addition, the quantity of all models increases from Z1 to Z3.

Table 4 Control of weak story irregularity

Models	Story	η_{cix}	η_{ciy}	Explanations
Model 1	Z	1.0	1.0	No weak story irregularity
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity(last story)
Model 2	Z	0.58	0.58	<0,6 weak story irregularity (sectional dimensions shall be increased)
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 3	Z	0.58	0.58	<0,6 weak story irregularity (sectional dimensions shall be increased)
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.78	1.78	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 4	Z	0.58	0.58	<0,6 weak story irregularity (sectional dimensions shall be increased)
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 5	Z	0.47	0.48	<0,6 weak story irregularity (sectional dimensions shall be increased)
	1	1.25	1.21	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 6	Z	0.50	0.53	<0,6 weak story irregularity (sectional dimensions shall be increased)
	1	1.17	1.1	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 7	Z	1.0	1.0	No weak story irregularity
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 8	Z	1.0	1.0	No weak story irregularity
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)
Model 9	Z	1.0	1.0	No weak story irregularity
	1	1.0	1.0	No weak story irregularity
	2	1.0	1.0	No weak story irregularity
	3	1.0	1.0	No weak story irregularity
	4	1.0	1.0	No weak story irregularity
	5	1.0	1.0	No weak story irregularity (last story)

Table 5.Control of soft story irregularity

Models	Story	Soft story irregularity factor and control of the irregularity according to soil classes											
		Z1 Soil class				Z2 Soil class				Z3 Soil class			
		η_{kix}	η_{kiy}	$R(\Delta_i)_{max}/h_i$	$(\theta_i)_{max}$	η_{kix}	η_{kiy}	$R(\Delta_i)_{max}/h_i$	$(\theta_i)_{max}$	η_{kix}	η_{kiy}	$R(\Delta_i)_{max}/h_i$	$(\theta_i)_{max}$
Model 1	Z	0.78	0.78	0.0092 < 0.02	0.021 < 0.12	0.77	0.77	0.0115 < 0.02	0.021 < 0.12	0.77	0.77	0.0159 < 0.02	0.021 < 0.12
	1	1.09	1.09			1.09	1.09			1.09	1.09		
	2	1.17	1.17			1.18	1.18			1.20	1.20		
	3	1.28	1.28			1.31	1.31			1.34	1.34		
	4	1.60	1.60			1.64	1.64			1.69	1.69		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 2	Z	1.65	1.65	0.0144 < 0.02	0.041 < 0.12	1.64	1.64	0.0181 < 0.02	0.041 < 0.12	1.64	1.64	0.0249 > 0.02 Soft story irregualrty	0.041 < 0.12
	1	1.23	1.23			1.24	1.24			1.24	1.24		
	2	1.22	1.22			1.22	1.22			1.24	1.24		
	3	1.35	1.35			1.35	1.35			1.38	1.38		
	4	1.69	1.69			1.70	1.70			1.72	1.72		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 3	Z	0.77	0.77	0.009 < 0.02	0.021 < 0.12	0.77	0.77	0.0112 < 0.02	0.021 < 0.12	0.76	0.76	0.0154 < 0.02	0.021 < 0.12
	1	1.09	1.09			1.09	1.09			1.09	1.09		
	2	1.17	1.17			1.17	1.17			1.18	1.18		
	3	1.21	1.21			1.23	1.23			1.26	1.26		
	4	0.99	0.99			1.02	1.02			1.06	1.06		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 4	Z	0.44	0.44	0.0156 < 0.02	0.042 < 0.12	0.43	0.43	0.0195 < 0.02	0.042 < 0.12	0.43	0.43	0.0268 > 0.02 Soft story irregularity	0.042 < 0.12
	1	2.04	2.04			2.04	2.04			2.05	2.05		
	2	1.32	1.32			1.33	1.33			1.35	1.35		
	3	1.32	1.32			1.35	1.35			1.38	1.38		
	4	1.56	1.56			1.61	1.61			1.67	1.67		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 5	Z	1.77	1.76	0.0147 < 0.02	0.042 < 0.12	1.77	1.76	0.0185 < 0.02	0.042 < 0.12	1.76	1.76	0.0255 > 0.02 Soft story irregularity	0.042 < 0.12
	1	1.14	1.14			1.14	1.14			1.15	1.15		
	2	1.20	1.20			1.21	1.21			1.22	1.23		
	3	1.34	1.34			1.35	1.35			1.37	1.37		
	4	1.69	1.69			1.70	1.70			1.72	1.72		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 6	Z	1.72	1.71	0.0146 < 0.02	0.041 < 0.12	1.72	1.71	0.0183 < 0.02	0.041 < 0.12	1.71	1.71	0.0252 > 0.02 Soft story irregularity	0.041 < 0.12
	1	1.17	1.17			1.17	1.17			1.18	1.18		
	2	1.21	1.21			1.21	1.21			1.23	1.23		
	3	1.34	1.34			1.35	1.35			1.37	1.37		
	4	1.69	1.69			1.70	1.70			1.72	1.72		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 7	Z	0.71	0.71	0.01 < 0.02	0.023 < 0.12	0.71	0.71	0.0125 < 0.02	0.023 < 0.12	0.70	0.70	0.0172 < 0.02	0.023 < 0.12
	1	1.16	1.16			1.16	1.16			1.16	1.16		
	2	1.21	1.21			1.22	1.22			1.23	1.23		
	3	1.28	1.28			1.31	1.31			1.35	1.35		
	4	1.60	1.60			1.64	1.64			1.69	1.69		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 8	Z	0.71	0.71	0.01 < 0.02	0.023 < 0.12	0.71	0.71	0.0125 < 0.02	0.023 < 0.12	0.70	0.70	0.0172 < 0.02	0.023 < 0.12
	1	1.16	1.16			1.16	1.16			1.16	1.16		
	2	1.21	1.21			1.22	1.22			1.23	1.23		
	3	1.28	1.28			1.31	1.31			1.35	1.35		
	4	1.60	1.60			1.64	1.64			1.69	1.69		
	5	0.0	0.0			0.0	0.0			0.0	0.0		
Model 9	Z	0.78	0.78	0.0092 < 0.02	0.021 < 0.12	0.77	0.77	0.0115 < 0.02	0.021 < 0.12	0.77	0.77	0.0159 < 0.02	0.021 < 0.12
	1	1.09	1.09			1.09	1.09			1.09	1.09		
	2	1.17	1.17			1.18	1.18			1.20	1.20		
	3	1.28	1.28			1.31	1.31			1.34	1.34		
	4	1.60	1.60			1.64	1.64			1.69	1.69		
	5	0.0	0.0			0.0	0.0			0.0	0.0		

Table 6 Required concrete classes and associated fundamental vibration period

Models	Adequate concrete classes Story						Period (T_1)
	Ground story	1st story	2nd story	3rd story	4th story	5th story	
Model 1	C30	C30	C30	C30	C30	C30	0.90
Model 2	C55	C30	C30	C30	C30	C30	1.12
Model 3	C30	C30	C30	C30	C30	C60	0.91
Model 4	C30	C55	C30	C30	C30	C30	1.14
Model 5	C65	C30	C30	C30	C30	C30	1.09
Model 6	C60	C30	C30	C30	C30	C30	1.10

- These results show that the design of RC buildings is quite important of weak story irregularity in terms of cost.
- Fundamental vibration period of the models with weak story irregularity is greater than that of the model with no the irregularity while base shear force of the model with the irregularity is lower than that of the model with no the irregularity. Besides, base shear force obtained from all models increases from Z1 to Z3.
- Relative story displacements of the models increase compared to that of model-1. It is very significant advantage for RC buildings with no weak story irregularity to have greater displacement rigidity than the RC buildings with the weak story irregularity.
- To prevent weak story irregularity, shear walls and diagonal bracing elements can be used.
- In current TEC, concrete strength is not considered in calculations related to weak story irregularity. It is recommended that concrete strength should be included in these calculations by taking the results obtained from this study.
- These findings in this study have shown that consideration of weak story irregularity at design level of RC buildings in the countries situated active earthquake zone such as Turkey is very important for rough construction costs.

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