Nonlinear Static Analysis of RC Buildings: Effects of Soil Type and Seismic Code Differences on Structural Performance

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Nonlinear Static Analysis of RC Buildings: Effects of Soil Type and Seismic Code Differences on Structural Performance

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Abstract

Reinforced concrete (RC) building construction remains predominant in Northern Cyprus, offering resilience against natural disasters when appropriately designed and implemented. The study presents a seismic analysis of RC building models across different soil classes, stories, and configurations, according to multiple seismic design codes: Eurocode 8 (EC8), Northern Cyprus Seismic Code 2015 (NCSC-2015), and Turkish Buildings Earthquake Code 2018 (TBEC-2018). This paper compares regular and irregular forms of Moment Resisting Frame (MRF) and MRF combined with Shear Walls (MRF+SW) systems in various configurations. These configurations include G+3, G+7, and G+11 for regular buildings, and only G+11 for irregular buildings. Pushover analysis using ETABSv18 was employed to assess the base shear, plastic hinge behavior, and displacement. The results indicate that the regularity of the structures enhances resistance and longevity compared to irregular configurations, with shear walls augmenting resistance against earthquake loads in both regular and irregular buildings. Furthermore, soil class emerges as a significant factor influencing results across the codes. While variations among the codes were not consistently observed, EC 8 and TBEC-2018 often appeared more conservative, with TBEC-2018 demonstrating greater adaptability to advanced technologies and a more detailed parameter consideration.

Keywords: earthquake; pushover analysis method; reinforced concrete; soil classes; seismic codes.

Introduction

Reinforced concrete structures are frequently seen worldwide due to the large number of stories they consist of and the high capacity they can take. Consequently, a comprehensive understanding of RC structure design is crucial, as failure in any component or joint can lead to catastrophic collapse, resulting in significant loss of life. Particularly, the consideration of earthquake loads in RC structure design has become paramount due to the substantial casualties often associated with seismic events.

While it's impossible to guarantee complete safety during earthquakes, adherence to seismic code regulations can substantially enhance building safety. For instance, the recent earthquake in Turkey and Northern Syria on February 6th, 2023, measuring 7.7 magnitude and followed by a 7.6 magnitude aftershock with over 9000 subsequent tremors, highlighted the consequences of neglecting code requirements. The failure to comply with seismic codes led to outcomes surpassing initial expectations.

In general, strict adherence to code regulations is imperative to ensure structural resilience. Furthermore, code standards must be periodically updated to facilitate earthquake-resistant building

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design. However, in the case of Turkish codes, the comprehensive update process can be lengthy (Aksoylu et al., 2020).

ETABS has garnered considerable recognition and undergone substantial evolution over a span exceeding three decades, as delineated by Mule et al. (2020). A plethora of prior scholarly investigations have directed their focus toward leveraging ETABS for conducting structural analyses. Furthermore, its amenability to accommodating various design codes has facilitated the seamless execution of analyses across diverse regulatory frameworks, owing to its comprehensive repository encompassing such codes.

Seismic activity poses a complex load on structures, necessitating precise analysis to predict structural response accurately (Kocer, 2021). This seismic movement is categorized into various grades based on intensity. The first grade represents low movement, typically resulting in minimal to no damage. The second grade signifies moderate movement, which may lead to some non-structural damage. Finally, the third grade denotes intensive movement, causing both structural and non-structural damage (Yassin & Sadeghi, 2023).

This study focuses on North Cyprus, which shares connected borders with South Cyprus. The two regions exhibit several similarities such as the environmental factors, geographical nature, soil type, etc. Despite these similarities, Northern Cyprus and Southern Cyprus adhere to different earthquake regulations, utilize distinct design codes, and consider various design parameters. Furthermore, Northern Cyprus imports certain materials from Turkey, aligned with TBEC-2018 standards. Despite existing studies comparing different earthquake codes, there is a scarcity of research pertaining to NCSC-2015. Thus, there is a necessity to compare EC 8, NCSC-2015, and TBEC-2018, as they all play integral roles or indirectly influence the same geographical area.

Long Beach region in Yeni Iskele and Gonyeli region in the capital Nicosia were selected for the study because of the different properties of their soil types, and their population growth. For example, the Long Beach region has alluvial soil while some locations in southern Turkey that were affected by the 6^{th} of February earthquake also have the same soil type. The three codes list this soil type as the softest soil class, while it amplifies the shaking of the ground during earthquakes significantly (Büyüksaraç et al, 2014).

The essential aim of the study is to compare the analysis outcomes of EC 8, NCSC-2015, and TBEC-2018, with the following objectives:

- Conducting seismic analysis of 3D regular and irregular MRF systems, and seismic analysis of regular and irregular MRF+SW systems employing the nonlinear static analysis method (Pushover analysis).
- Comparing the resulting values of base shear and displacement obtained from the seismic analysis.
- Observing the occurrence of plastic hinges to identify the weak connections within the structure.

Literature Review

In the context of structural design practices in Cyprus, the NCSC-2015 standard is predominantly applied within the jurisdiction of Northern Cyprus, albeit supplemented by the importation of construction materials from Turkey, as inferred from references within TEC-2007. Conversely, the EC8 standard finds prevalence in Southern Cyprus. Despite this, there remains a notable absence of direct comparisons between these codes in existing literature. Existing research has shown significant differences and inconsistencies, highlighting the need for a thorough investigation across different factors like soil type, number of storeys, and geographical locations. Therefore, this study seeks to strengthen and expand on previous findings, improving the reliability and applicability of the conclusions drawn from the analysis.

The following are some previous studies:

- A comparative study between EC8 and NCSC-2015 codes by Hamed & Resatoglu, 2019. The outcomes of the study showed that the base shear for EC8 and NCSC-2015 were similar.

- Another study by Aksoylu et al, 2020 conducted a comparison of TEC-2007, TBEC-2018, and ASCE 7-16. The study analyzes structures with a different number of floors using the linear equivalent method. The outcomes of the study state that the maximum base shear force was obtained at TEC-2007 for 3 and 5-story buildings, whereas the maximum base shear force was obtained at TBEC-2018 for 7 and 9-story buildings.
- A study conducted by Atmaca et al, 2019 pointed out that the TBEC-2018 introduces two new earthquake analysis methods, namely Nonlinear and Linear, which were not present in TEC-2007. Moreover, TBEC-2018 offers several advantages, including specifying the earthquake site and the soil type with six classes instead of four. Additionally, it accounts for both long and short periods of acceleration coefficients. Ultimately, the study's findings indicate that the 2018 code is more cautious compared to the previous one.

Seismicity of Cyprus

A predicted period of 475 years is estimated for a rock condition earthquake return. The studied area, Cyprus, is surrounded by three tectonic plates: the Anatolian plate is moving towards the west, the African plate is moving towards the north, and the Arabian plate is also moving towards the north at a faster pace. These plates are interconnected by fault lines, including the East Anatolian fault line, which has two extension fault lines traversing through the island. Previous studies, such as those by Cagnan et al. (2010), have suggested that the East Anatolian Fault line has two active extensions extended towards the north and south of Cyprus. These fault lines span across several countries, including Türkiye, Cyprus, Syria, Palestine, Jordan, and Lebanon, as depicted in Fig. 1.

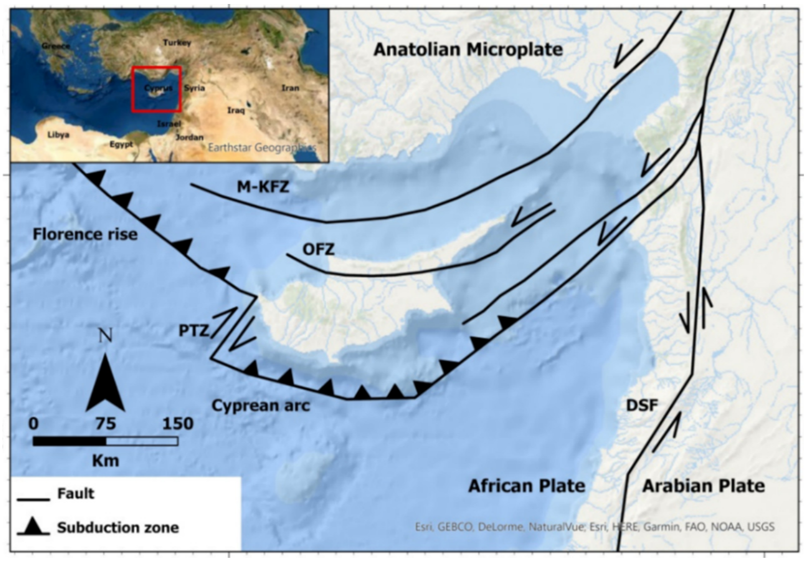


Fig. 1

The Anatolian Plate, the Arabian Plate, and the African Plate that surrounded the fault lines by (Evelpidou. 2022)

Seismic Design Codes

Codes serve as the foundation of design regulations, providing engineers with essential guidelines for their calculations. It is crucial for codes to undergo continuous study and updating over time to ensure they evolve and remain relevant. In the realm of civil engineering, earthquake codes have been established for quite some time. In Turkey, for instance, earthquake codes date back to as early as 1940, with the most recent version being in 2018, marking the 10th iteration (Işık, 2021).

NCSC-2015 and EC8 have a seismic zone map that shows different areas based on earthquake severity, where each area has a specific peak ground acceleration (PGA). The map is divided into four seismic zones according to NCSC-2015 and three seismic zones according to EC8, where

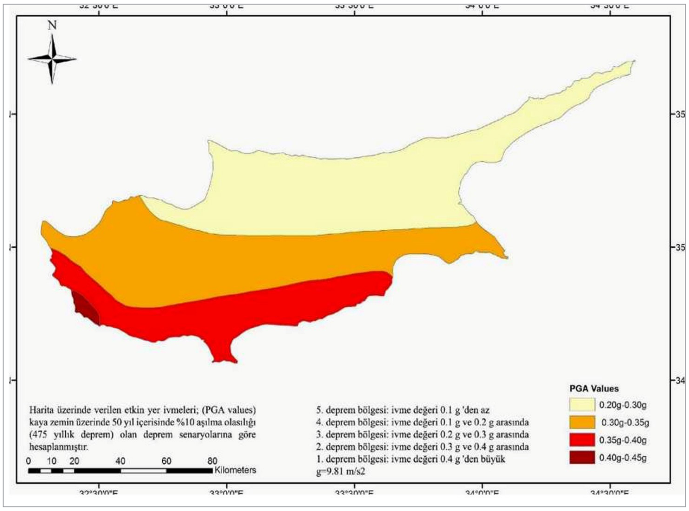


Fig. 2

NCSC-2015 Seismic Map of Cyprus (NCSC-2015)

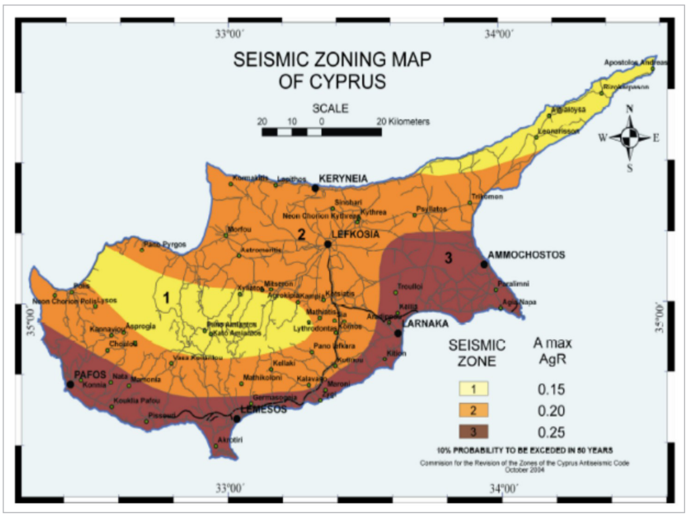


Fig. 3

EC 8 Seismic Map of Cyprus (Cyprus National Annex, Eurocode 8)

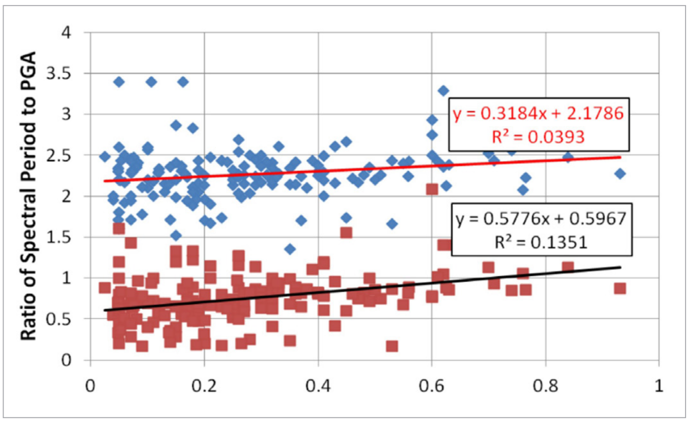


Fig. 4

The spectral period to PGA ratio from the seismic hazard databases. (Lubkowski & Aluisi, 2012)

the selected locations in this study are located in the first zone in NCSC-2015 and the second zone in EC8 as shown in Fig. 2 and Fig. 3.

The TBEC-2018 introduces changes in the process compared to NCSC-2015 and EC8. Instead of PGA values, it now employs short-period spectral acceleration (Ss) and long-period spectral acceleration (S1). Furthermore, it's the first code to incorporate horizontal and vertical design spectra, appearing to be better aligned with modern technologies. It's launched with more detailed information for each province in Turkey. Unfortunately, this code and its map are specific to Turkey, but the approach can be adapted and applied to other codes in different regions.

To conclude, numerous new concepts have been added in TBEC-2018 such as the classification of building height, earthquake ground motion level, vertical elastic design spectrum, earthquake design class, and the application of earthquake hazard on a regional basis was the most important addition to this code (Büyüksaraç, 2022).

The ratio of spectral acceleration with respect to PGA can be obtained by Fig. 4. The graph in Fig. 4 demonstrates the ratio among PGA and spectral acceleration of return periods from 100 years to 1000 years obtained from over 50 studied databases. (Lubkowski & Aluisi, 2012).

The ratio between Ss and PGA is represented by the blue diamonds, and therefore, by identifying the PGA, Ss can be obtained from this equation:

$$S_S/PGA= 0.3386*PGA + 2.1696$$

In contrast, the ratio between S1 and PGA is represented by the red squares, and therefore, by identifying the PGA, S1 can be obtained from this equation:

$$S_1/PGA = 0.5776*PGA + 0.5967$$

Nonlinear Static Analysis Method (Pushover Analysis)

The pushover method is a technique that involves pushing a structure to its maximum resistance point, taking into account earthquake properties such as spectral acceleration, soil type, PGA, and others (Yassin, 2023). In this method, the building has two potential outcomes:

1. If a building reaches a collapsed state, therefore, this building is unsafe, and the applied earthquake loads have pushed the structure till it collapses.
2. If a building reaches its maximum limit without collapsing during an earthquake, it means that the structure has endured the maximum earthquake loads without showing any critical hinges. This indicates that the building is considerably safe and that the applied earthquake loads have pushed the structure to a specific limit.

This method evaluates the structure's seismic performance and the real strength. Therefore, the curve of base shear force and displacement (Capacity Curve) can be acquired after running the pushover analysis. This curve shows the start point and the maximum point that the structure has reached whether it collapsed after this point or not as shown in **Fig. 5.**

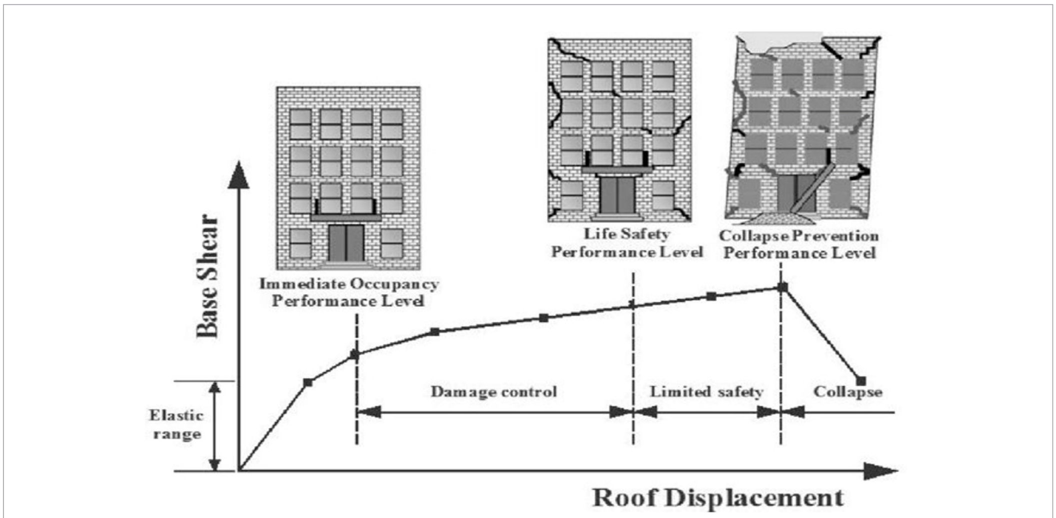


Fig. 5

Capacity Curve with Demonstration of Building Performance Level and Damage State (Abd-Elhamed & Mahmoud, 2016)

The previous figure describes the seismic performance of a building during an earthquake in four steps Operational, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), respectively, and each step has a worse state compared to the previous step.

Methodology

Several case studies were analyzed according to these earthquake regulations EC 8, NCSC-2015, and TBEC-2018, targeting to obtain different outcomes for strengthening the comparative study.

In this study, floor-plan of regular and irregular structures have been selected with specific details. For instance, the height of the ground floor is 3.2m, while the height of the remaining floors is 3m. The beams and columns were modeled as frame elements, whereas solid slabs and shear walls were modeled as shell elements. In addition, Plastic hinges were placed at beams and columns after 10% and 90% of the total length. to obtain accurate outcomes while using the pushover method and noticing the occurrence of plastic hinges, that practically predict the first member to fail.

The modeling of foundations was intentionally omitted from the scope of this study and was simply treated as fixed within the software to streamline and expedite the process, given the large number of buildings being modeled. Comparing the outcomes of the selected codes and determining the most effective one for future studies was the main purpose of this study. Consequently, this assumption was uniformly applied across all selected models. However, it is important to note that the results could be influenced and altered if alternative foundation types were utilized. In a 2015 study by Somwanshi and Pantawane, it was revealed that buildings with fixed bases exhibit no displacement at their base, whereas those with base isolation exhibit discernible displacement. This implies that the application of this assumption to all models could uniformly impact the results of each model.

The ETABS models were executed following a systematic procedure:

1. Material properties were selected.
2. Cross-sections for columns, beams, shear walls, and slabs were added.
3. Models were drawn.
4. Pattern loads including dead load, super dead load, live load, wind load, and earthquake load were incorporated.
5. Loads were applied to the members, excluding earthquake loads.
6. Plastic hinges were defined at the corners.
7. Nonlinear Static (pushover) load cases were addressed as follows:

   A. The first load case considered dead load only.

   B. The second load case considered super dead load with a scale factor of 1 and live load with a scale factor of 0.25. This case initiated after the completion of the first load case.

   C. The third load case considered earthquake acceleration for both x and y directions with a scale factor of -1. Additionally, this case commenced after the second load case, and P-Delta effects were considered.

8. The analysis was executed.

P-Delta effect occurs when horizontal earthquake loads induce drift on structural elements, resulting in an eccentricity of the gravity loads along the vertical column axis. This induced eccentricity amplifies internal moments, consequently influencing the first-order moment (Istiono et al., 2022), as depicted in Fig. 6.

In this study, the analyzed models consist of two systems: the Moment Resisting Frame (MRF) system and the combination of MRF with Shear Walls (MRF+SW) system. These systems were in regular form for low-rise, mid-rise, and high-rise structures and assessed with a shear wall span length of 1.5m. Additionally, irregular forms were considered solely for high-rise structures. Moreover, to ensure a robust comparison, the member sizes were kept consistent across all structures within each story for all three selected codes.

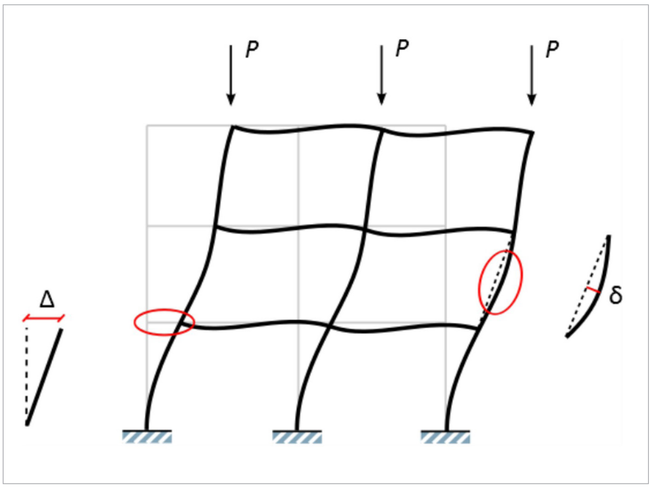


Fig. 6
P-Large Delta (P-Δ) & P-Small Delta (P-δ)

Furthermore, two locations were selected: Long Beach region in Yeni Iskele and Gonyeli in Nicosia. These locations exhibit distinct soil characteristics, as detailed in Tables 2, 3, and 4. Ground surveys aimed at earthquake resilience on the island reveal that the coastal area of Yeni Iskele has weak bearing capacity and is susceptible to liquefaction (Selcukhan & Ekinci, 2023). This region is characterized by soft alluvial soil, classified as class D in NCSC-2015 and class E in EC8 and TBEC-2018. Conversely, Nicosia city's soil varies, with the north featuring rocky medium soil, the center consisting of soft rock or very dense soil, and the south comprising solidified soil groups (Dindar, 2021). The Göneyli region, located in Nicosia, is characterized by stiff soil, classified as class C across all codes. Despite these differences, both locations were chosen due to their notable population growth and urbanization trends, as depicted in **Fig. 7**.

A. Regular Structures

These structures should be symmetrical in principle direction and have no significant discontinuity in plan or lateral configurations. In addition, members must continuously run from the highest point to the foundation without interruptions (Yadav & Hazari, 2022). Additionally, the structure can be described as having vertical configurations and continuities in both plans (Naveen et al., 2019). For this study, a typical regular floor-plan was chosen, representing residential buildings with three configurations of story: G+3, G+7, and G+11. The dimensions of the configurations are 25 meters on the Y axis and 25 meters on the X axis, and each direction contains 5 bays with a bay length of 5 meters..

- **Fig. 8** and **Fig. 9** display MRF model in regular form.

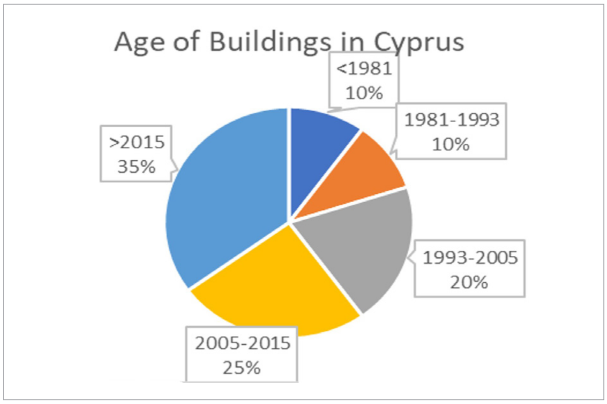


Fig. 7

Age of buildings in Northern Cyprus

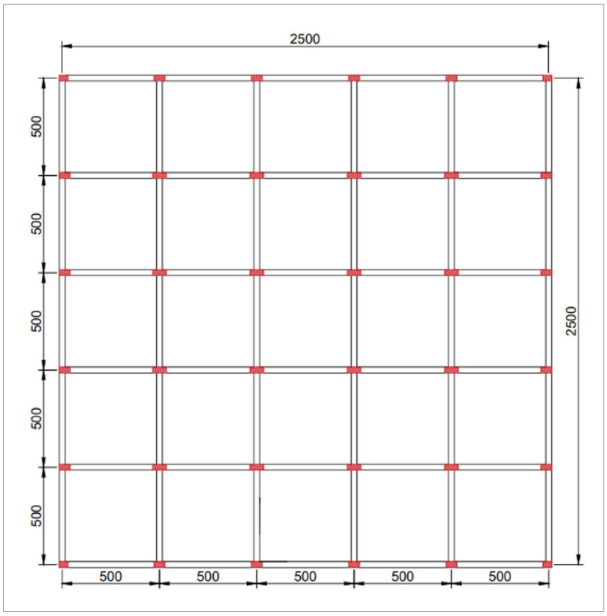


Fig. 8

Floor-plan for MRF model in Regular Form

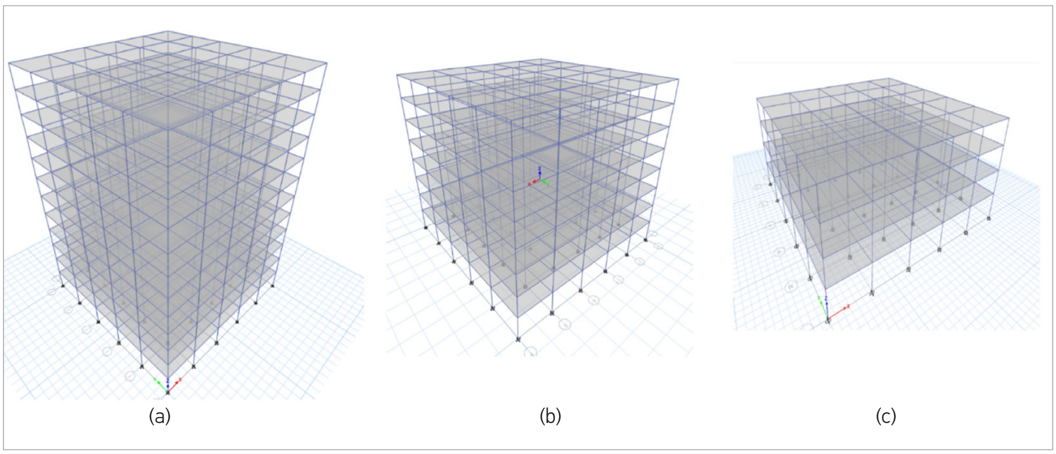


Fig. 9

3D view for MRF model in regular form. a) G+11 Story, b) G+7 Story, c) G+3 Story

_ **Fig.** 10 and **Fig.** 11 display MRF+SW model in regular form.

Fig. 10

Floor-Plan for MRF+SW model in Regular Form

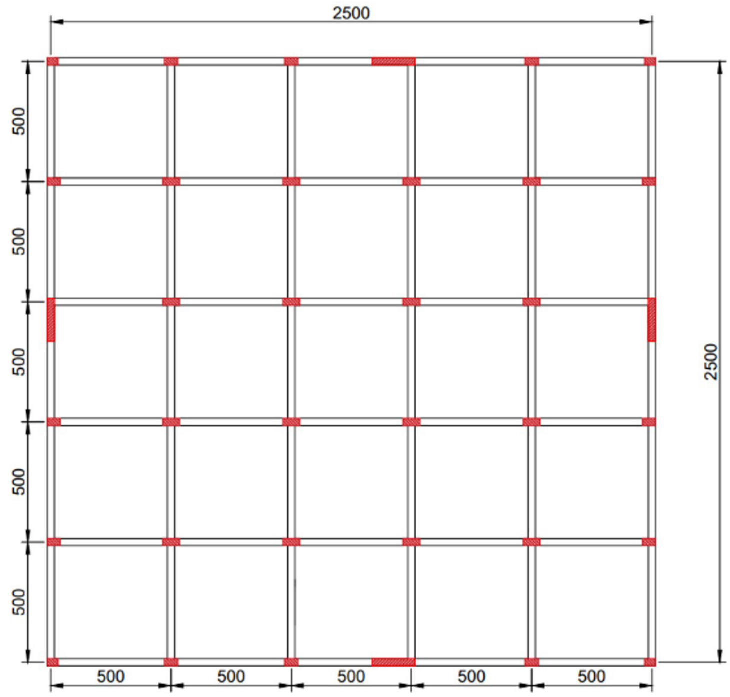
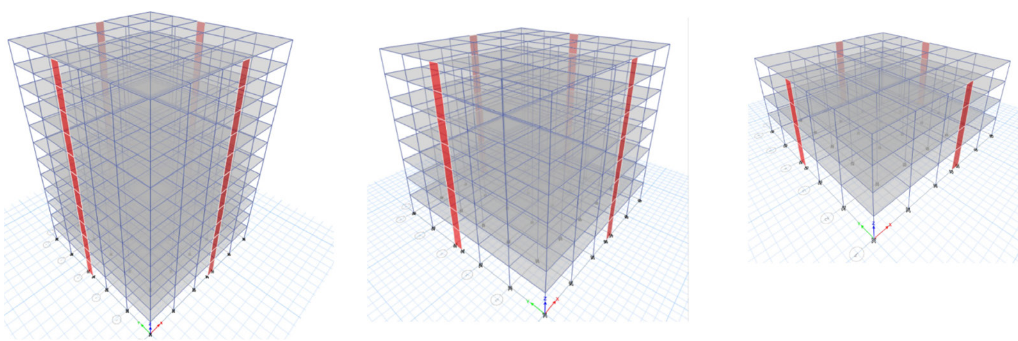


Fig. 11

3D view for MRF+SW model in regular form a) G+11 Story, b) G+7 Story, c) G+3 Story



B. Irregular Structures

These structures have a sudden physical discontinuity, either in plan, lateral configuration, or both, as they are kept unsymmetrical in the principal direction. (Yadav & Hazari, 2022). As a consequence, irregularity affects the performance of the structure during earthquakes (Naveen et al, 2019). In simpler terms, irregular structures lack symmetry either in the X or Y coordinates, or both. Despite being recognized as weaker compared to regular structures in previous studies, they remain prevalent due to factors such as geographical constraints and other considerations. A residential building with an irregular plan was chosen for this study. It comprises eleven stories (G+11) and has dimensions of 25 meters on both the X and Y axes. The building features discontinuous five bays, each with a length of 5 meters.

_ **Fig. 12** and **Fig. 13** display MRF model in irregular form.

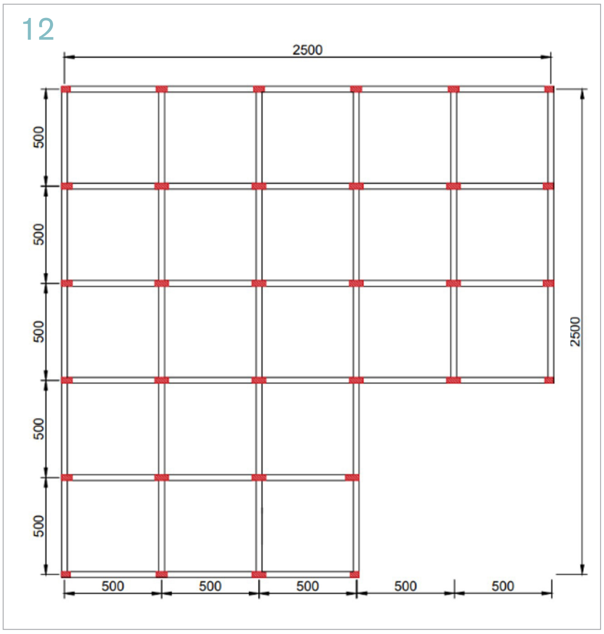


Fig. 12
Floor-Plan for MRF model in Irregular Form

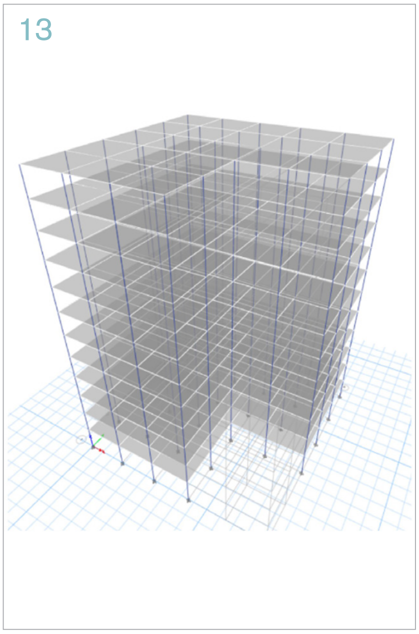


Fig. 13
3D view for MRF model in Irregular Form

_ **Fig. 14** and **Fig. 15** display MRF+SW model in irregular form.

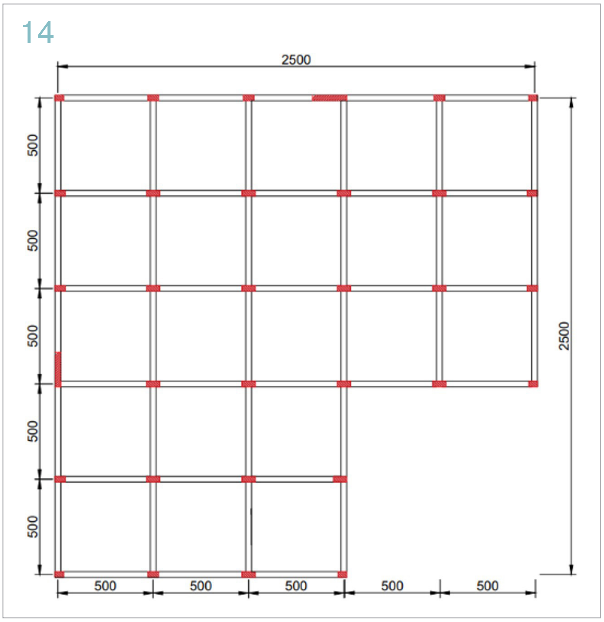


Fig. 14
Floor-Plan for MRF+SW model in Irregular Form

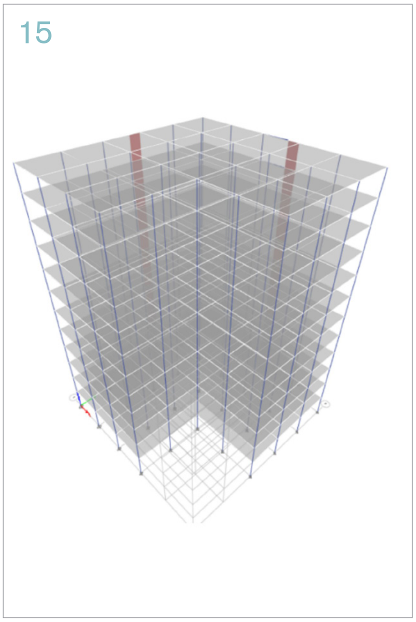


Fig. 15
3D view for MRF+SW model in Irregular Form

Design Criteria

A total of 48 models underwent analysis using the Pushover method within the ETABSv18 software. Uniform application of live load, dead load, and super dead load, along with seismic loads determined by code parameters, was maintained across all models. The accompanying design criteria are delineated below.

A. Material Properties:

The materials selected for the study were chosen to meet the requirements of all three codes. For instance, the minimum concrete strength specified by NCSC-2015, EC8, and TBEC-2018 is

C20, C20/25, and C25, respectively. Additionally, following the 1999 earthquakes, the Turkish Ready Mixed Concrete Association recommended the use of C30 concrete in earthquake-prone areas (Zengin et al., 2023). Therefore, for this study, C30 concrete, which possesses a compressive strength of 30 MPa, was selected, with other concrete parameters determined accordingly based on this strength grade.

The codes have different reinforcement steel classes. NCSC-2015 contains three steel classes S220, S420, and S500, while EC8 and TBEC-2018 have different steel classes. However, the only common steel class among the codes is S420. Therefore, this study uses the S420 steel grade.

For brick walls, the approach differs as they can be chosen based on the prevalent brick wall type in the region. Hence, an average value was selected for the unit weight of brick walls. The **Table 1** displays the chosen parameters for concrete, steel, and brick walls for the study:

Table 1

The material properties of concrete, steel and walls

Parameter	Value
Minimum Tensile Strength (Fu)	520 MPa
Concrete Modulus of Elasticity	25743 MPa
Steel Modulus of Elasticity	210000 MPa
Compressive Strength (*f'c*)	30 MPa
Yield Stress (Fy)	420 MPa
Unit weight of Steel	78.5 kN/m^3
Unit weight of Concrete	30 kN/m^3
Unit weight of Brick walls	16 kN/m^3

B. Section Properties

The buildings were analyzed using both regular and irregular models. These models included beams with dimensions of 250mm x 500mm, 180mm solid slabs, 200mm internal clay brick walls, 250mm shear walls, 250mm external clay brick walls, and columns ranging from (300mm*300mm) to (300mm*800mm) depending on the floor and the position of the column, for example, the columns at the top floor are the smallest, and their size increase gradually to the bottom floor. In addition, the corner columns are the smallest, and the size increases in the external columns, where the center columns are the biggest.

C. Load Properties

The selected loads were considered according to the codes and unit weight of the materials as follows: live load (2kN/m^2), Super Dead load (2.5 kN/m^2), external walls (12 kN/m), internal walls (9.6 kN/m), where dead load and wind load considered from the software. In addition, earthquake loads were taken according to each code as shown in part D.

D. Earthquakes Properties

The characteristics of earthquakes are appraised in accordance with the criteria of each code and the particular locations specified in this study. These characteristics are delineated in the tables provided below.

Table 2

Earthquake properties of NCSC-2015 for the selected locations

Description		Long Beach region in Yeni Iskele	Gonyeli region in Nicosia
Seismic Zone		1	1
PGA		0.3	0.3
Behaviour factor (R)	MRF	8	8
	MRF+SW	7	7
Importance factor (I)		1	1
Soil type		D	C

Description		Long Beach region in Yeni Iskele	Gonyeli region in Nicosia
Seismic Zone		2	2
PGA		0.2	0.2
Lower limit of the period (TB)		0.15	0.2
Upper limit of the period (TC)		0.5	0.6
Behaviour Factor q	MRF	5.85	5.85
	MRF+SW	5.4	5.4
The beginning of the constant displacement (TD)		2	2
Correction Factor		1	1
Importance factor (I)		1	1
Soil Factor		1.4	1.15
Soil type		E	C

Table 3

Earthquake properties of EC8 for the selected locations

Description		Long Beach region in Yeni Iskele	Gonyeli region in Nicosia
Long-Period Transition Period		8	8
Spectral Acceleration for short period (Ss)		0.6795	0.6795
Spectral Acceleration for 1 second (S1)		0.2259	0.2259
Response Modification (R)	MRF	8	8
	MRF+SW	7	7
System Overstrength (D)	MRF	3	3
	MRF+SW	2.5	2.5
Importance factor (I)		1	1
Site type		ZE	ZC

Table 4

Earthquake properties of TBEC-2018 for the selected locations

Results and Discussion

This section illustrates the obtained results from the Pushover such as base shear force, displacement, and the occurrence of plastic hinges were explained and presented as graphs based on the regularity and irregularity of structures. The results were organized by building type in the following:

1. MRF Models in Regular Form

The base shear force, displacement, and occurrence of plastic hinges for the MRF models in regular form were determined across three building codes, three different story structures, and two soil types with varying numbers of stories.

A. Base Shear Force & Displacement

The figures depicted in **Fig.16** and **Fig. 17** delineate the pushover curve (capacity curve), illustrating the correlation between base shear force and displacement for MRF models in regular form. These models encompass various codes, differing numbers of stories, and diverse soil classes.

Based on the preceding graph charts, both NCSC-2015 and EC8 exhibited marginal increases, not exceeding 5%, in the soft soil class across all the models. In contrast, TBEC-2018 demonstrated an increase in the soft soil class for all models.

In TBEC-2018, there was a modest 6% increase in base shear for the G+11 model in the soft soil class. However, this increase escalated in the G+7 models, reaching 12% for base shear and 18%

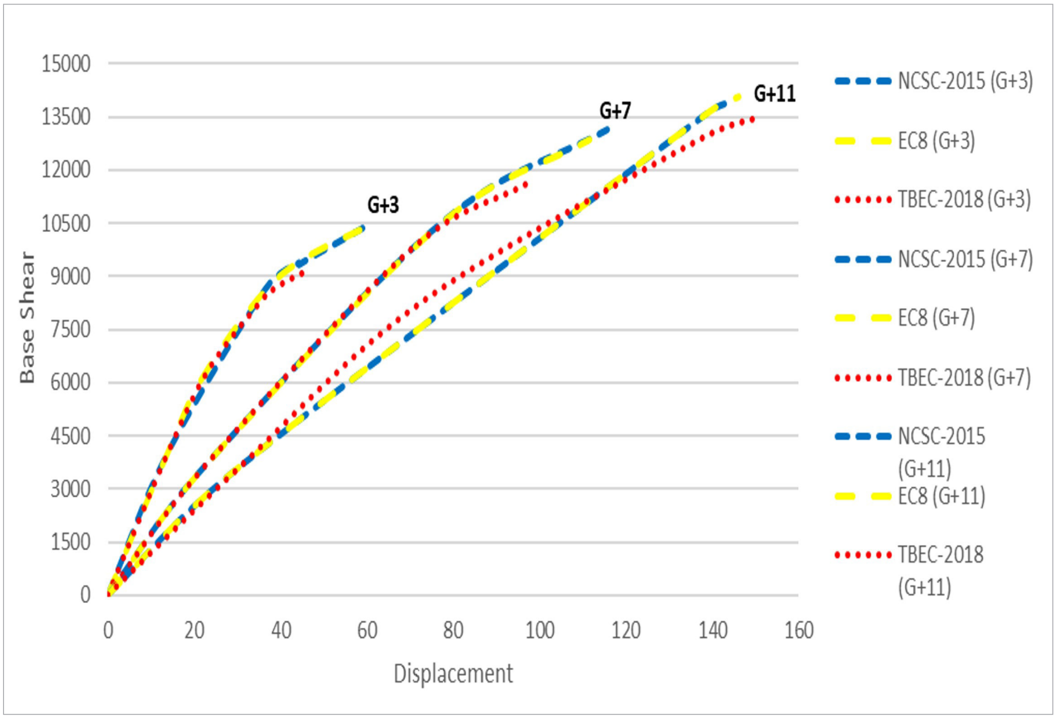


Fig. 16

The pushover curves for MRF models in regular form, medium soil type

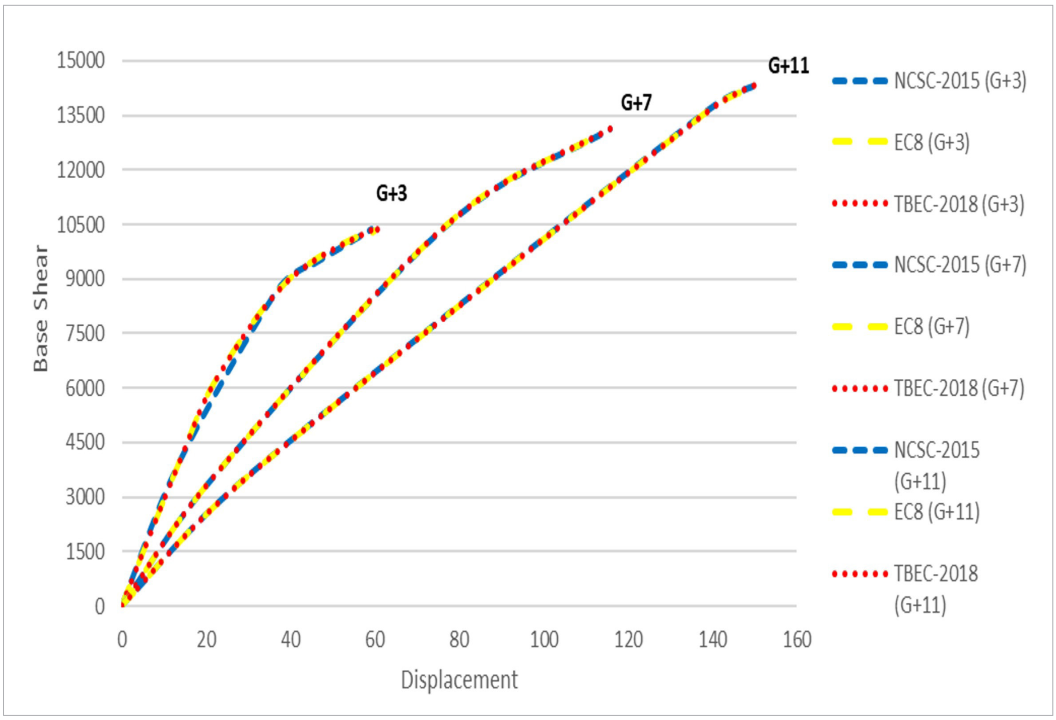


Fig. 17

The pushover curves for MRF models in regular form, soft soil type

for displacement. Moreover, the G+3 models experienced a slight rise in the soft soil class, reaching 14% for base shear and 23% for displacement.

B. Plastic Hinges

The presence of plastic hinges plays a critical role in determining the structural integrity of buildings during earthquakes. In many instances, plastic hinges were observed in various locations throughout the buildings, with some exceeding the critical plastic (CP) state, particularly in the ground and first stories. Consequently, all the models in the selected locations are at risk and are not fortunate enough to remain standing during earthquakes.

C. Summary

EC8 and NCSC-2015 exhibited only a slight disparity between medium and soft soil classes, whereas TBEC-2018 demonstrated a more significant and realistic discrepancy, with a notable increase in the soft soil class.

The regular MRF models appeared to be vulnerable in earthquake-prone areas, as indicated by the increase in base shear and displacement in soft soil class models. Moreover, in some instances, these values remained comparable to those in medium soil class models.

Furthermore, the majority of plastic hinges occurred on the first stories, including CP state hinges. Consequently, these models appear to be at substantial risk, as failure in any of these plastic hinges could potentially result in the collapse of the entire structure in practice.

2. MRF+SW Models In Regular Form

The base shear force, displacement, and occurrence of plastic hinges for the MRF+SW models in regular form were obtained for three building codes, three different story structures, and two soil types with varying numbers of stories.

A. Base Shear Force & Displacement

The figures depicted in Fig. 18 and Fig. 19 delineate the pushover curve (capacity curve), illustrating the correlation between base shear force and displacement for MRF+SW in regular form. These models encompass various codes, differing numbers of stories, and diverse soil classes.

The graph lines indicate that across all cases, there are relatively consistent results among medium soil and soft soil types. However, while base shear forces show a slight increase from G+3 to G+11, the displacement experiences a significant rise over the same range.

In NCSC-2015 and EC8 models, no notable distinctions were observed between medium and soft soil classes; their performances appeared similar.

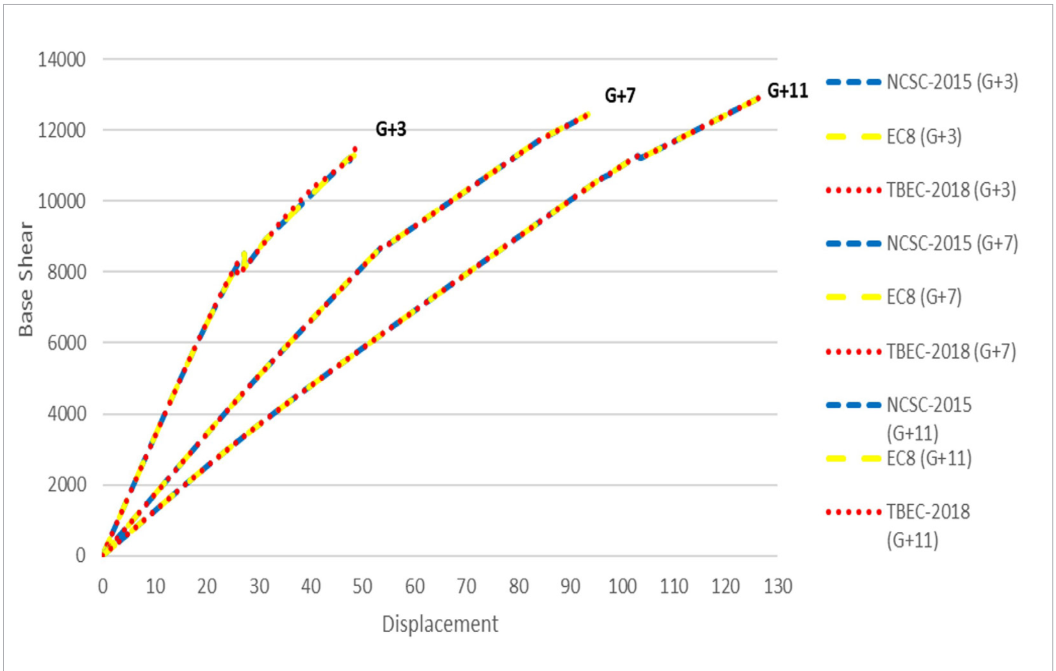


Fig. 18

The pushover curves for MRF+SW models in regular form, medium soil type

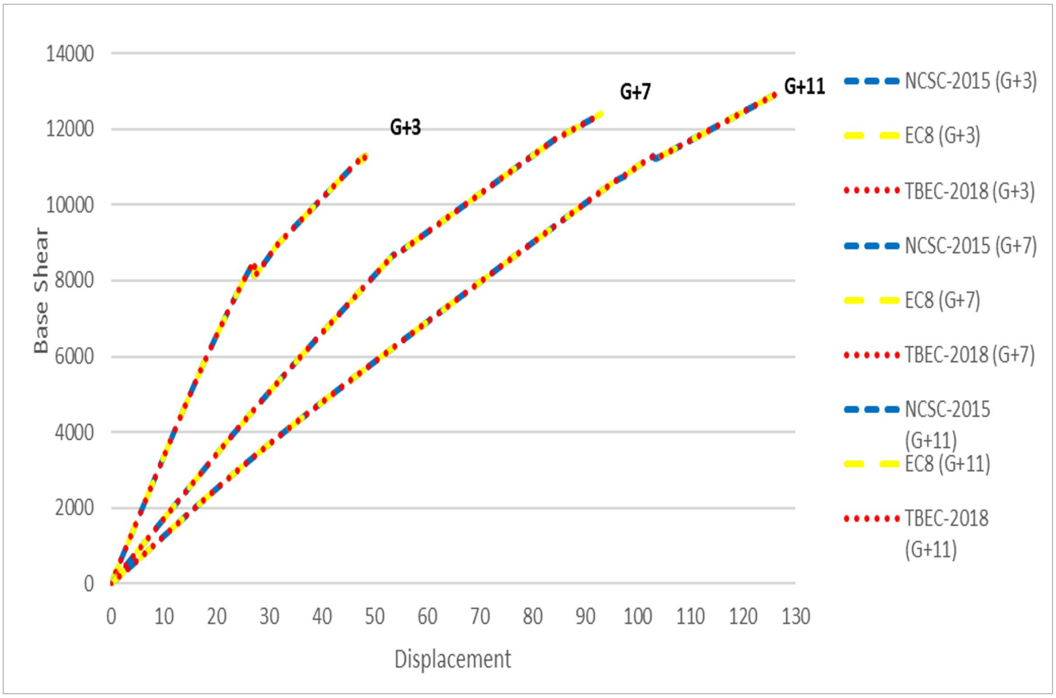


Fig. 19

The pushover curves for MRF+SW models in regular form, soft soil type

Contrastingly, TBEC-2018 exhibited a slight decrease in base shear and displacement by approximately 5% in the soft soil class for G+3 models. Additionally, only one plastic hinge, reaching the critical plastic (CP) state, was identified in the G+3 soft soil class model. Consequently, this model may reach failure sooner than the corresponding medium soil class model, which could explain the observed decrease rather than an increase.

B. Plastic Hinges

The occurrence of plastic hinges was consistent across all codes, with one plastic hinge reaching the critical plastic (CP) state in all G+3 models on the ground floor. Additionally, some plastic hinges with IO and LS states occurred in all G+7 and G+11 models on both the first and ground floors. Consequently, G+7 and G+11 configurations appeared to exhibit greater safety in this regard compared to G+3 configurations.

C. Summary

NCSC-2015 and EC8 depicted no difference between medium and soft soil classes, while TBEC-2018 depicted a slight base shear decrease in the soft soil of G+3. Although the results showed only one difference, MRF+SW models seemed to perform better compared to MRF, especially in G+7 models and above.

3. MRF Models In Irregular Form

The base shear force, displacement, and occurrence of plastic hinges for the MRF models in irregular form were obtained for three seismic design codes, and two soil types, specifically for high-rise structures.

A. Base Shear Force and Displacement

Fig. 20 delineates the pushover curve (capacity curve), illustrating the correlation between base shear force and displacement for high-rise MRF models in irregular form. These models encompass various codes and diverse soil classes.

The preceding line graph reveals that the peak base shear and displacement were observed in NCSC-2015. However, there was no notable change in the results for EC8 and TBEC-2018. Notably,

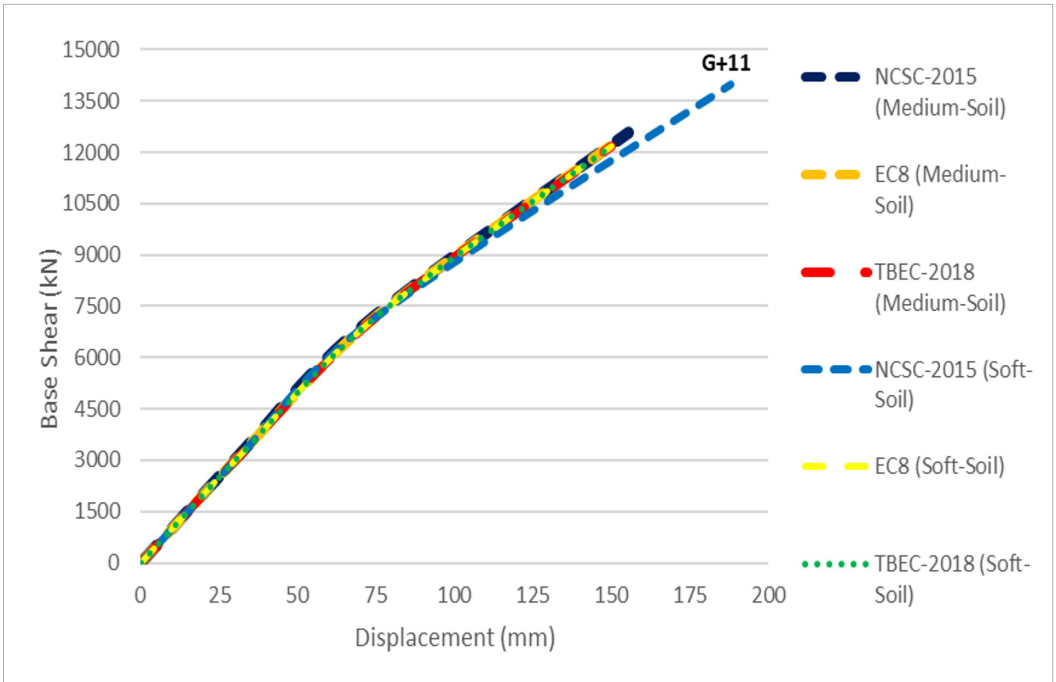


Fig. 20

The pushover curves for MRF models in an irregular form, medium and soft soil types

in the soft soil class, NCSC-2015 exhibited a 10% increase in base shear force and a 17% increase in displacement. Consequently, models designed according to NCSC-2015 exhibited greater resilience and endured for a longer period before collapse compared to those designed according to other codes.

B. Plastic Hinges

Plastic hinges reaching the critical plastic (CP) state were observed in all models. In NCSC-2015, these hinges appeared on the first stories for the soft soil type, while fewer hinges were observed in the medium soil class, appearing only on the ground and first floors.

Conversely, EC8 and TBEC-2018 did not exhibit a distinction between medium and soft soil classes. However, CP state plastic hinges were predominantly located on the ground and first floors.

C. Summary

The models seemed unsafe in all cases, but in EC8 and TBEC-2018 the consideration of danger occurrence was higher and the collapse seemed to happen earlier than NCSC-2015. The irregular MRF models appeared very weak and unable to resist seismic loads.

4. MRF+SW Models in Irregular Form

The base shear force, displacement, and occurrence of plastic hinges for the MRF+SW models in irregular form were obtained for three seismic design codes, and two soil types, specifically for high-rise structures.

A. Base Shear Force and Displacement

Fig. 21 delineates the pushover curve (capacity curve), illustrating the correlation between base shear force and displacement for high-rise MRF+SW models in irregular form. These models encompass various codes and diverse soil classes.

The results depicted in this graph showed minimal variation among all models, with differences, if any, not exceeding 1%.

Primarily, the similarity in results can be attributed to the timing and location consistency of critical plastic hinge occurrences.

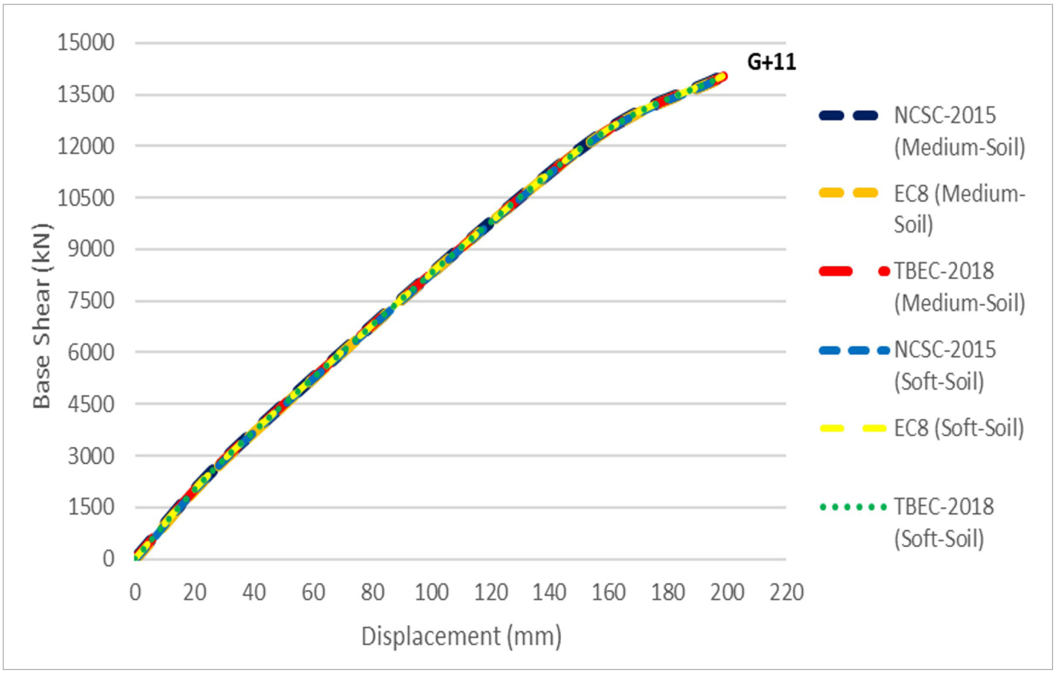


Fig. 21

The pushover curves for MRF+SW models in an irregular form, medium and soft soil types

B. Plastic Hinges

All models faced plastic hinges occurrence with a CP state in the first three stories. Therefore, these structures appeared weak and couldn't resist the applied earthquake loads.

C. Summary

The models displayed vulnerability and are unlikely to remain standing under the imposed earthquake conditions. Even though the 1.5 m span length shear walls may provide some resistance, it appeared to be insufficient.

Moreover, the simultaneous occurrence of critical plastic hinges at consistent locations suggests that the codes in this scenario predicted collapse at the same juncture.

Conclusions

1. MRF regular models:

Base shear force and displacement exhibited an increase from G+3 to G+11 structures. Particularly in TBEC-2018, the transition from medium to soft soil had a more realistic impact on base shear and displacement. However, across all structures, the presence of critical hinges indicated that they were unsafe.

2. MRF+SW regular models:

Base shear force and displacement increased as the number of stories rose from G+3 to G+11 buildings. The results appeared consistent for both soil types in EC8 and NCSC-2015, while TBEC-2018 decreased slightly from medium soil to soft soil type for G+3 structures. Overall, all models seemed to remain stable and capable of withstanding the applied seismic loads.

3. MRF irregular models:

The increase from medium soil to soft soil class in base shear force and displacement was observed in NCSC-2015, while EC8 and TBEC-2018 displayed consistent results for medium and soft soil types. However, the occurrence of critical hinges was predicted in EC8 and TBEC-2018 earlier than NCSC-2015, suggesting that structures evaluated by NCSC-2015 may withstand more before collapsing. Nevertheless, all models appeared unsafe due to critical hinges presence.

4. MRF+SW irregular models:

For all codes, base shear and displacement showed no variation between soil classes, and critical hinges occurred at identical locations. Consequently, all structures were deemed unsafe due to the presence of critical hinges.

5. Primary conclusions:
   - The codes produced identical outcomes when:
     1. Models are unsafe but has not collapsed according to the applied seismic loads.
     2. Models are safe, and no occurrence of plastic hinges.
   - The shear walls play a main role in mitigating seismic load impact.
   - In general, models with regular shapes are more resilient to earthquakes compared to buildings with irregular shapes.
   - The first three stories of a building are typically the most critical, as plastic hinges tend to occur in them predominantly.
   - The findings underscore the importance of soil class as a significant factor influencing the results across different seismic design codes.
   - It has been observed that the impact of earthquakes on the models has not changed significantly between new and old regulations. However, this outcome may differ depending on structures with diverse geometric characteristics and soil types.
   - NCSC-2015 divides Cyprus into four earthquake regions with corresponding PGA values, irrespective of the condition of local sites. In contrast, TBEC-2018 provides structure-specific data based on coordinates and introduces a revised approach by incorporating an updated seismic hazard map.
   - TBEC-2018 appears to be more comprehensive and adapted to advanced technologies, considering parameters in a more detailed manner.
   - Based on the findings, variations among the codes were not always evident. However, most of the time EC8 and TBEC-2018 tended to be more conservative.
   - The main difference between TBEC-2018 and NCSC-2015 is the updated implementation of the seismic Hazard Map. In TBEC-2018, specific seismic features based on coordinates from this map are used to define short-period and long-period spectral acceleration for each location. Therefore, it would be beneficial to develop a new map for Cyprus using the updated procedure introduced in TBEC-2018.
   - Despite the codes not indicating significant differences in the results, TBEC-2018 appeared to show more logical results and predict the danger earlier as this code also considers more parameters and specific details. Therefore, this study can state that TBEC-2018 is the most appropriate code compared to NCSC-2015 and EC8.

Recommendations

Based on the findings of this study, the following recommendations are proposed for future research:

1. Future studies should consider comparing seismic design codes while also incorporating specific types of foundations within the scope of the study, such as mat foundations or base-isolated foundations.
2. It would be beneficial to conduct additional studies focusing on various types of soil to further explore their impact on structural behavior under earthquake loads.
3. Utilizing 3D models that closely resemble real-world structures is recommended for future studies, despite potential challenges in comparison. Such models provide increased accuracy and realism.

4. Future research endeavors can explore the development of a new earthquake map for Cyprus, similar to the approach adopted in Turkey, with coordinates providing site-specific seismic hazard data.
5. Researchers are encouraged to carefully select a subset of models and analyze them using multiple seismic analysis methods. This approach can yield more robust and accurate results, enhancing the understanding of structural response to seismic events.

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