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Effect of Different Types of Bracing System and Shear Wall on the Seismic Response of RC Buildings Resting on Sloped Terrain

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Abstract

Several factors have been affecting the urban design areas, leading to the construction of reinforced concrete (RC) buildings. Buildings on sloped terrains have been gaining increased popularity, especially from architectural peers. The vulnerability of constructions to seismic loads on sloped terrains increases due to mass and vertical irregularity, which in turn increases the torsional moments as well as shear forces. To control the effect of the seismic loads, many systems have been implemented, including shear walls and bracing systems. The objective of this work is to evaluate the effects of different strengthening systems and to identify the most suitable one for seismic load resistance. This paper studies the behavior of buildings with different strengthening systems applied to seismic loads using ETABS V18.1 and response spectrum analysis. A parametric study for these buildings has been performed to evaluate the effect of seismic loads on them. A dynamic analysis of the buildings in terms of shear forces, displacement, drift, fundamental time period, base shear, and story stiffness was carried out. The results demonstrated that the use of a combined strengthening system increased the stiffness and stability of the models and the resistance of RC buildings to seismic loads on sloped terrains.

Keywords: Seismic Loads; Shear Walls; Bracing; Response Spectrum Analysis; ETABS.

1. Introduction

Due to the scarcity of land in urban areas and its high popularity, it has led to the development of buildings on sloped terrains. Building on sloped terrain has many problems, such as structural and construction problems due to the different structural behaviors. Previous research presented that the sloped structure develops torsional moments as these buildings are non-symmetric, which will increase the eccentricity of the building [1].

Many researchers worked on sloped terrain buildings and presented the problems involving this type of building and introduced different techniques for modelling and seismic load analysis. This research presented the compatibility concept of analysis that subdivides translational and torsional loads in setback structures that are involved in determining the center of rigidity [2], and presented studies that included analytical and experimental data on the effect of dynamic and static design requirements for buildings [3]. It also presented a simple dynamic analysis approach for sloped buildings by considering one degree of freedom for each floor in a translational direction. Other provided methods were based on the analysis of the transformation of mass matrices and stiffness about a vertical axis [4]. Researchers also presented a simple three-dimensional approach for elastic seismic analysis of asymmetrical and irregular sloped structures, using the action of a rigid floor diaphragm and comparing it with the analysis method taking into consideration the flexibility of the floor, and found similar results [5-7]. Researchers found that the short frames of the sloped terrain buildings have higher values of the base shear in their study of the step-back and setback buildings [8, 9],

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other researchers studied the translational fixation of column and foundation under seismic loads to present the suitable size of the building plan for building on steep terrain [10] and carried-out research on the behavior of building on steep terrain [9].

Although there is much research about the behavior of buildings on steep terrain, more research is needed to represent the actual behavior of the buildings, where some researchers studied the seismic loads' effects on multi-story RC framed shear wall buildings [11]. This study showed that shear walls affect the lateral strength of tall buildings but have less effect on lateral rigidity. On the other hand, shear walls for less-height buildings have a high effect on lateral stiffness but less effect on lateral force. A study of the effect of the shear wall position and size on the attracted forces revealed that the higher dimension of shear walls will increase the horizontal forces resisted by that shear wall [12]. Also, the location of the shear wall can significantly reduce the displacement due to seismic loads. Others presented the effect of the increase in the shear wall dimension and its effect on enhancing the performance of the building by reducing the displacements under seismic loads [13]. A study was performed using ETABS software to present the effect of seismic loads on different criteria such as base shear story drift and displacement [14].

Some researchers used STAD-Pro to study the static and dynamic analysis of buildings [15]. Others presented a study on buildings on level ground and sloped terrain using ETABS software with and without shear walls under seismic loads, where the research studied the displacement of the top story, story drift, base shear, and time period, and according to that study, it was found that the appropriate position for the shear wall when building on sloped terrain is at the building corners [16, 17]. A study on the seismic response of RC-framed buildings resting on hill slopes was performed to study the displacement of the top story, story drift, base shear, and time period [18]. Another study presented the effect of the position of steel bracing in L-shaped reinforced concrete buildings under lateral loading. Where the study of the inter-story drift, displacements, base shear, fundamental time period, torsional irregularity ratio, and the capacity ratio of the columns was carried out [19].

Few studies have been undertaken to understand the behavior of buildings on hill slopes. A study research compared the seismic performance positioned at the corners with core and walls L-shear as well as steel tube column filled with concrete and concluded that the use of shear walls reduces the fundamental time period and the lateral displacement at various locations [20]. Another study performed the seismic analysis using time history next to a shallow slope and found that the construction of buildings near the shallow slope increases the slop instability and deformation [21]. Another study on the mass irregularity effect on different story buildings was performed at different seismic zones to compare the story displacements and drift in these zones [22]. Seismic loads cause more damage to buildings on sloped terrain in comparison to the same buildings on flat terrain [23].

It can be seen from the literature review that very little work has been performed to investigate and analyze the effect of seismic loads on RC buildings on sloped terrain using a combined strengthening system. The majority of research works performed building analysis using a single strengthening system, such as shear wall or bracing. The presented work aims to investigate and analyze the effect of seismic loads on RC buildings on sloped terrain using a combined strengthening system by applying the analysis and comparing the responses of the buildings in terms of shear forces, displacement, drift, fundamental time period, base shear, and story stiffness. The objective of this work is to evaluate the effect of different strengthening systems on a structure on clopped terrain subjected to seismic loads and also to identify the most suitable strengthening system for seismic load resisting. To investigate the structural behavior changes due to seismic loads when structures are strengthened by different straightening systems on sloped terrain. Analyze the structural response of the different parameters such as displacement, shear force, story drift, and base shear for the investigated configuration such as building frame and different strengthening systems on sloped terrain.

2. Seismic Behavior of R.C. Buildings on Sloped Terrain

Many researches presented the slope response under the seismic loads mainly depends on the temporal and spatial seismic forces distribution in the soil, which mainly depends on the seismic load's characteristics and the soil's mechanical properties [24-26]. For the design of building foundations and to ensure that it is safe the design must fulfill essential requirements such as:

- The soil or rock geotechnical capacity surrounding the design foundations is safe against failure;
- The settlements should be acceptable under the different loading statics or dynamics loads;
- The slope stability for the area of the designed footings;
- The constructions should anticipate problem solutions.

The process of construction on sloped terrain is different from that on flat terrain since buildings on sloped terrain will have a torsional effect as these buildings are irregular and unsymmetrical in both vertical and horizontal plans, which means that extra consideration should be provided for the construction on sloped terrain [27]. Also, the construction of buildings on sloped terrain with frame systems only showed that the building frames with shorter lengths experienced more damage than the longer frames when applying the seismic loads for the same story building [28].

3. Analysis Method

A 10-story 3D building on sloped terrain with different strengthening systems is modeled to study the effect of seismic loads using the response spectrum analysis method using ETABS 18.1. The frame material is concrete which is assumed homogenous, elastic, and isotropic with Poisson's ration 0.2 and modulus of elasticity 25 KN/mm^2 and the steel yield stress 420MPa. The rigid diaphragms have been assigned to all floor systems. The foundation supporting system for all the models has been used as fixed. The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.

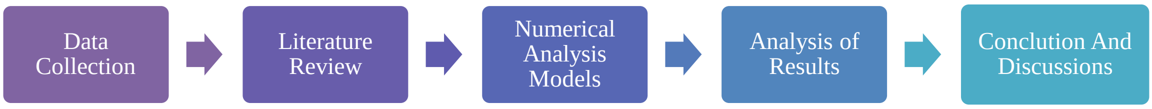


Figure 1. Research Methodology Flowchart

4. Structural Modelling

4.1. Geometry

The building model presented in Figuer1 has 4 bays in the X-axis direction and 6 bays in the Y-axis direction and the width of the bay is 4 m and 5 m. The high-rise Rc. building is a residential building with 10 floors and a 3.0m story height. The building plan is symmetrical in both X and Y directions to avoid the effect of the irregular torsion. The elements of the building are modelled using ETABS software. The columns have a uniform size of 60 cm × 60 cm, the dimensions of the beams are 45cm × 60 cm, the thickness of the Shear Wall is 20 cm, and the bracing is angle L-section 20cm × 20cm. The response spectrum analysis method was adopted as per the Saudi building code for the Medina zone and soil type B.

4.2. Geometrical Properties

Three-dimensional 10 multi-storeyed building space frame modelled with the same geometrical and material properties have been modelled that involves the plane terrain and sloped terrains with different systems. The analysis for the seismic loads has been performed by using the space frames, bracing, shear walls and system of shear wall and bracing. The analysis of the seismic loading was carried out using the response spectrum analysis approach method using ETABS 18.1 and the different seismic parameters such as story drift, story stiffness, top story displacement, story shear, and the fundamental time period.

4.3. Models Specifications

Table 1 and Figure 2 present the models' specifications and plan layout of the studded models, respectively.

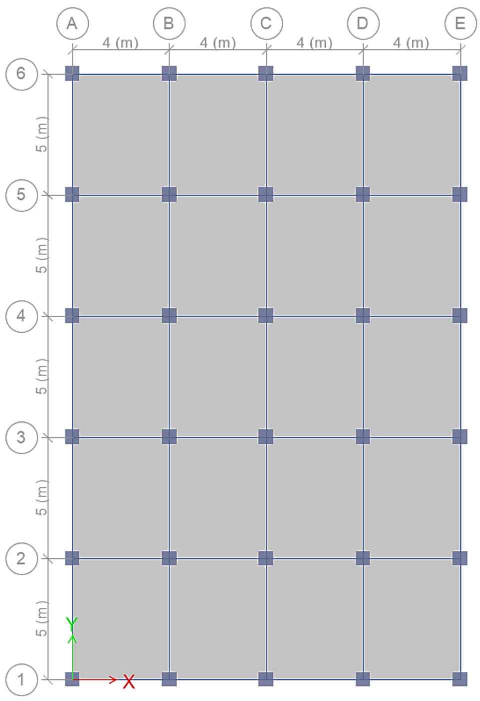


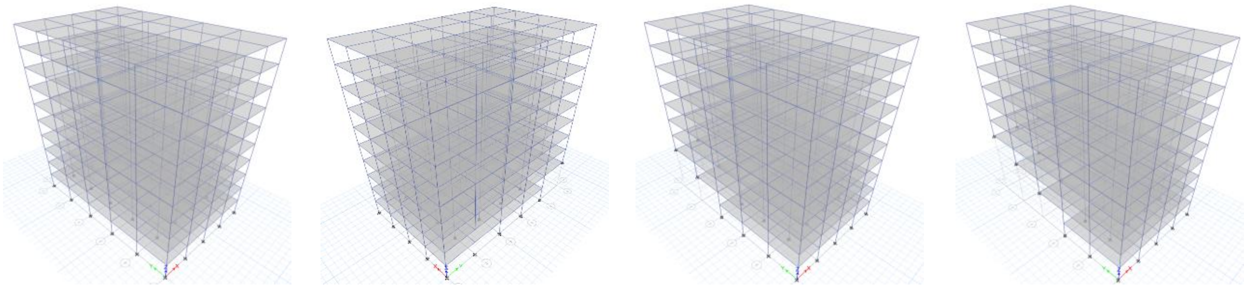
Figure 2. Typical Plan Layout

Table 1. Models' specifications

Model Parameter	Value
Bayes number in X direction	4
Bayes number in y direction	5
Story Hight	3
Slab type	Flat Slab
Slab thickness	200 mm
Building importance factor	1
Shear wall thickness	250 mm
Concrete Grade	M 30

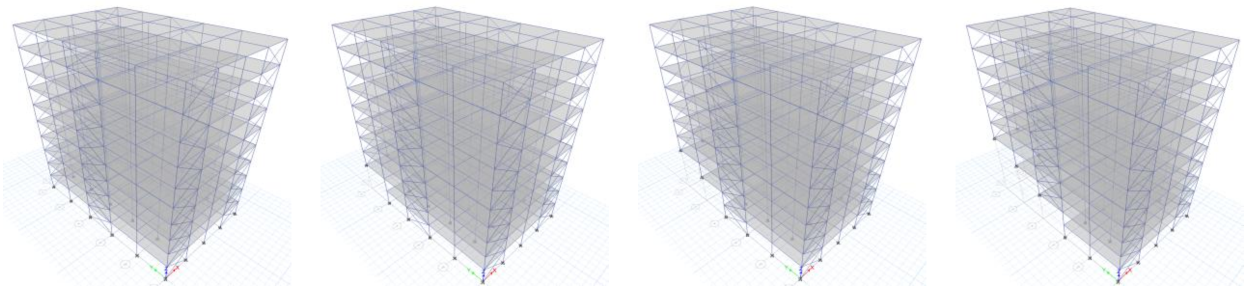
Figure 3 presents the 3D models for the R.C. High-rise building without strengthening systems and different lateral resisting system with different sloped terrains.

3D models for the R.C. High-rise building without strengthening systems with different sloped terrains.



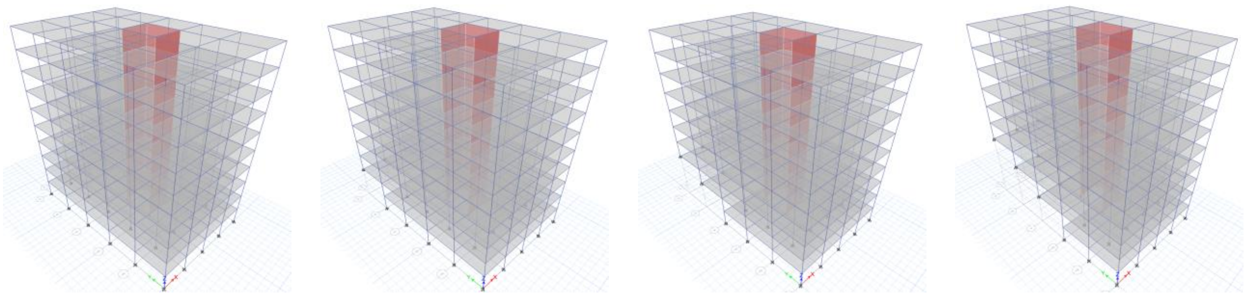
Flat Terrain. Sloped Terrain-1. Sloped Terrain-2. Sloped Terrain-3.

3D models for the R.C. High-rise building with bracin6g strengthening systems with different sloped terrains.



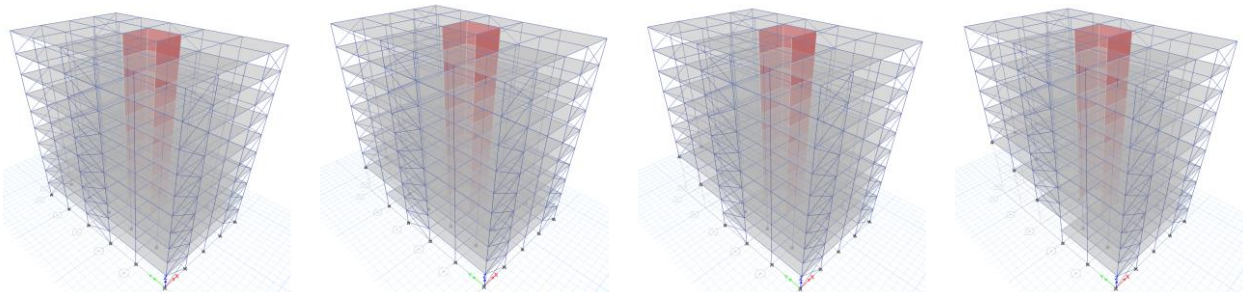
Flat Terrain. Sloped Terrain-1. Sloped Terrain-2. Sloped Terrain-3.

3D models for the R.C. High-rise building with a shear wall strengthening system with different sloped terrains.



Flat Terrain. Sloped Terrain-1. Sloped Terrain-2. Sloped Terrain-3.

3D models for the R.C. High-rise building with shear wall and bracing strengthening systems with different sloped terrains.



Flat Terrain. Sloped Terrain-1. Sloped Terrain-2. Sloped Terrain-3.

Figure 3. 3D models for High-rise buildings with and without lateral resisting system

4.4. Displacement for the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 4 to 7 presents the displacement of the different models for the flat terrain and different sloped terrain.

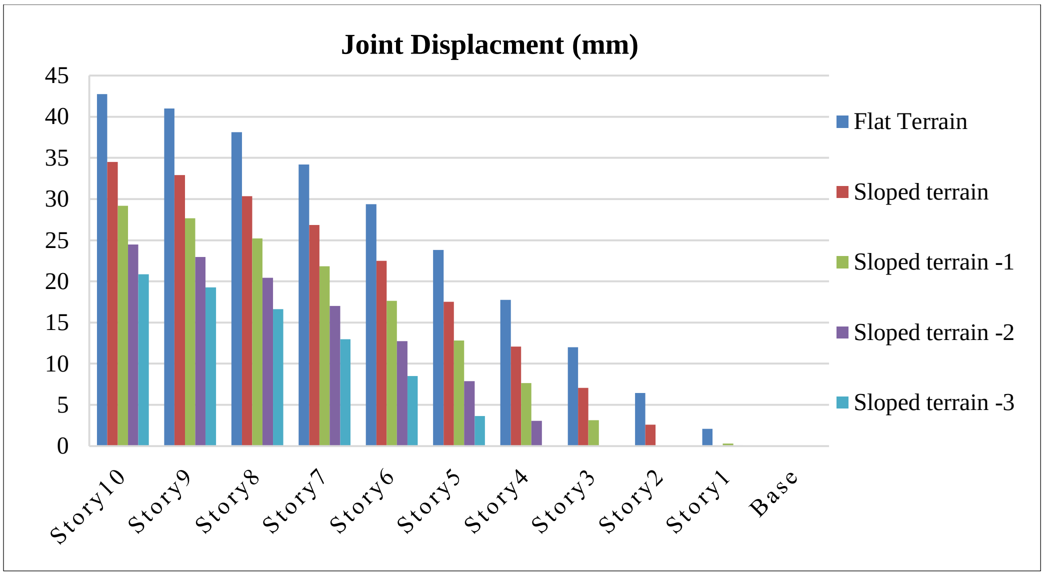


Figure 4. Joint displacement for models with different sloped terrain without strengthening systems

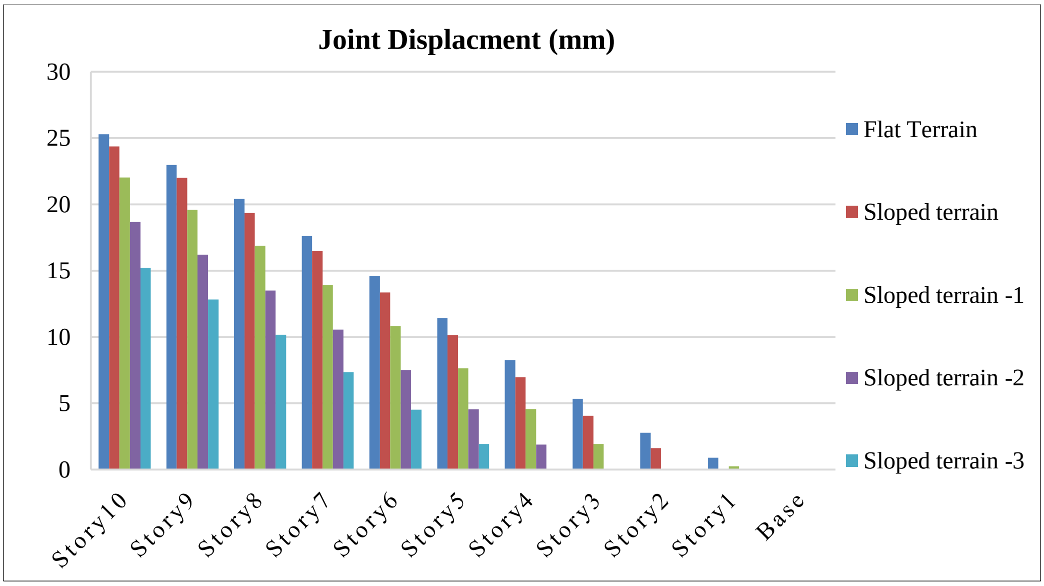


Figure 5. Joint displacement for models with different sloped terrain with shear walls systems

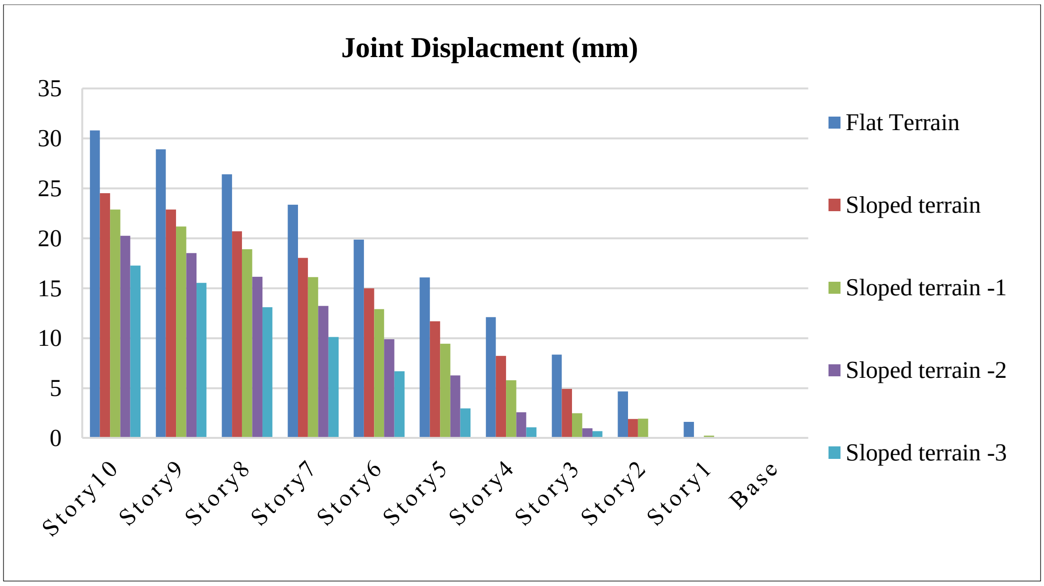


Figure 6. Joint displacement for models with different sloped terrain with a bracing system

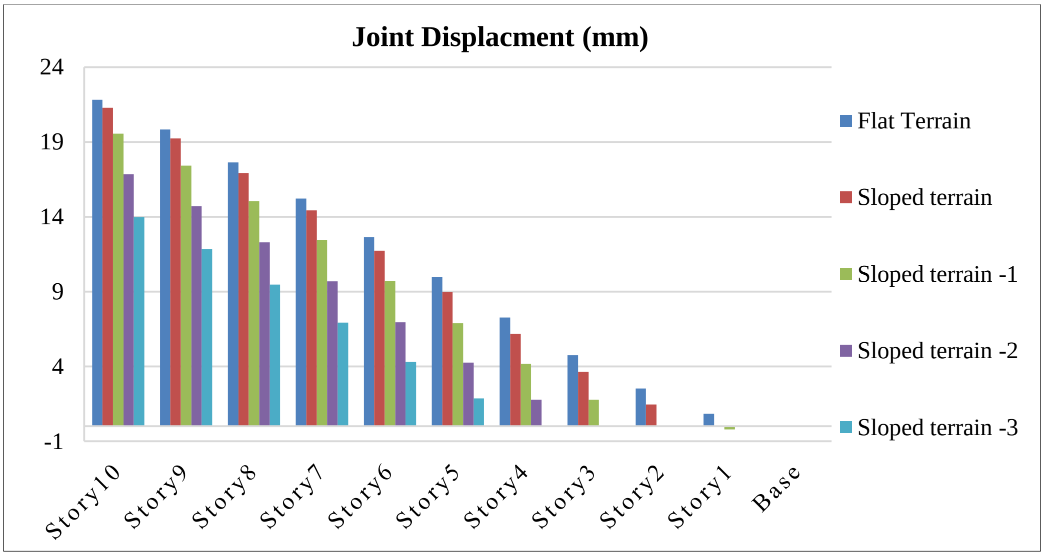


Figure 7. Joint displacement for models with different sloped terrain with shear walls and bracing systems

4.5. Story Drift for the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 8 to 11 presents the story drift of the different models for the flat terrain and different sloped terrain.

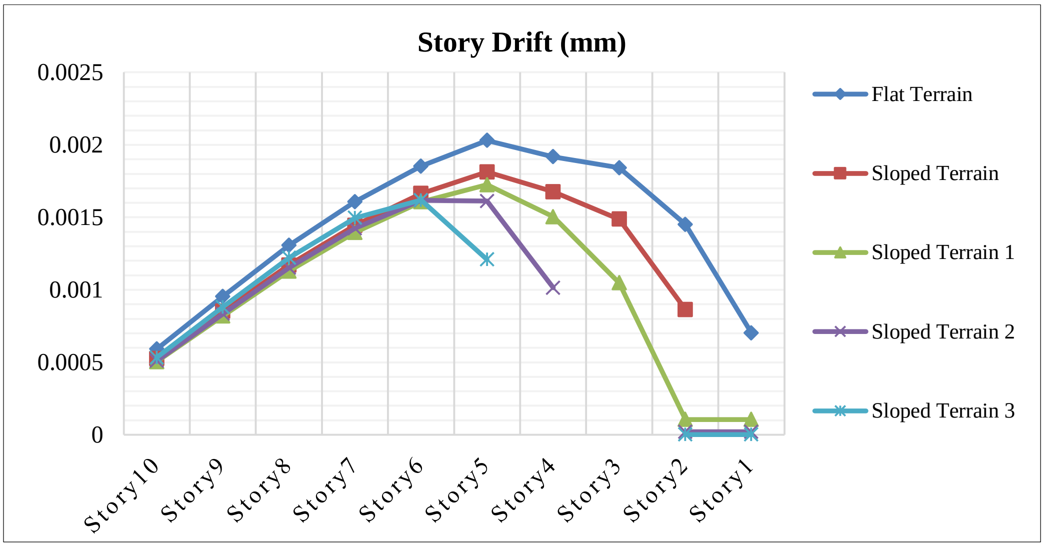


Figure 8. Story drift for models with different sloped terrain without strengthening systems

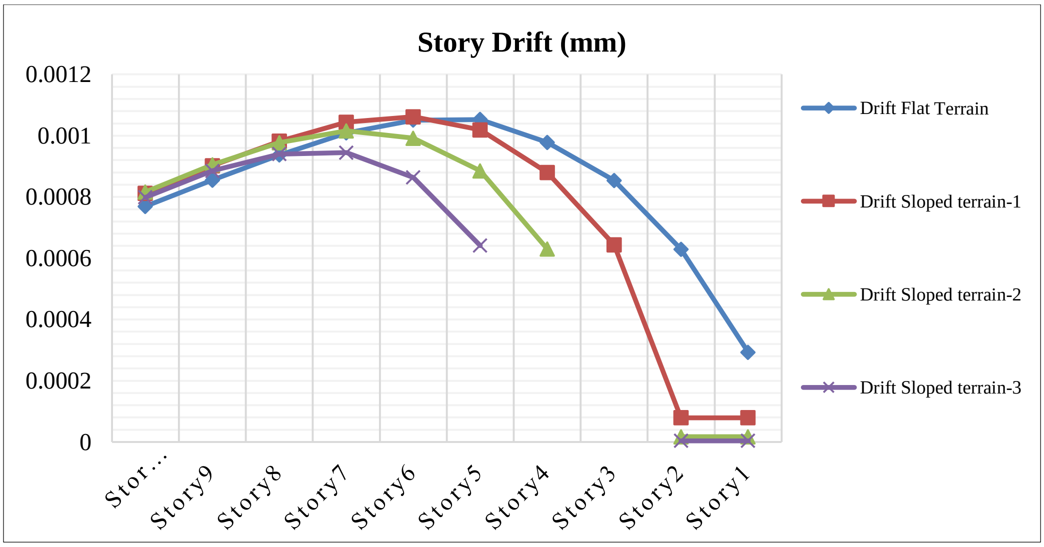


Figure 9. Story drift for models with different sloped terrain with shear walls systems

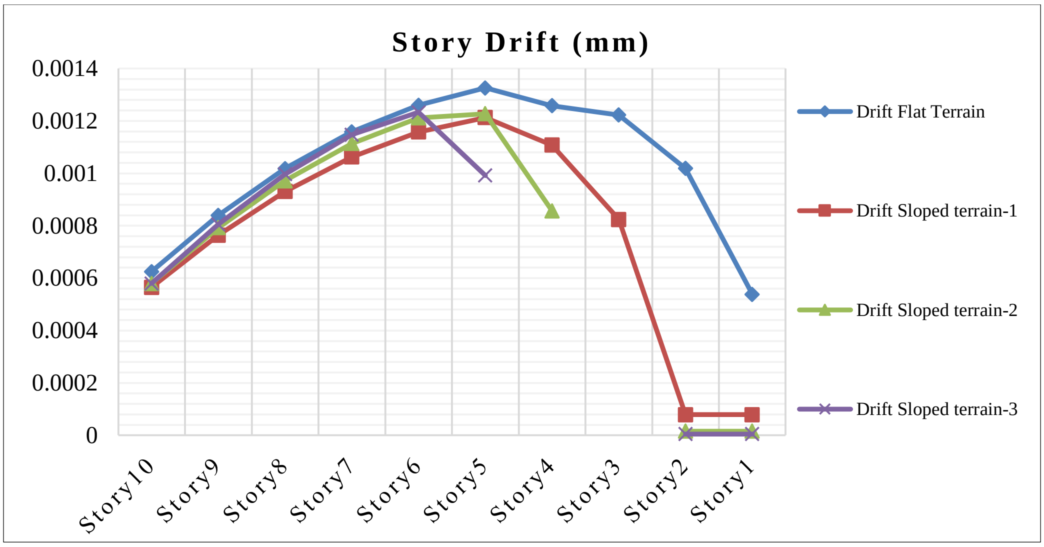


Figure 10. Story drift for models with different sloped terrain with Bracing systems

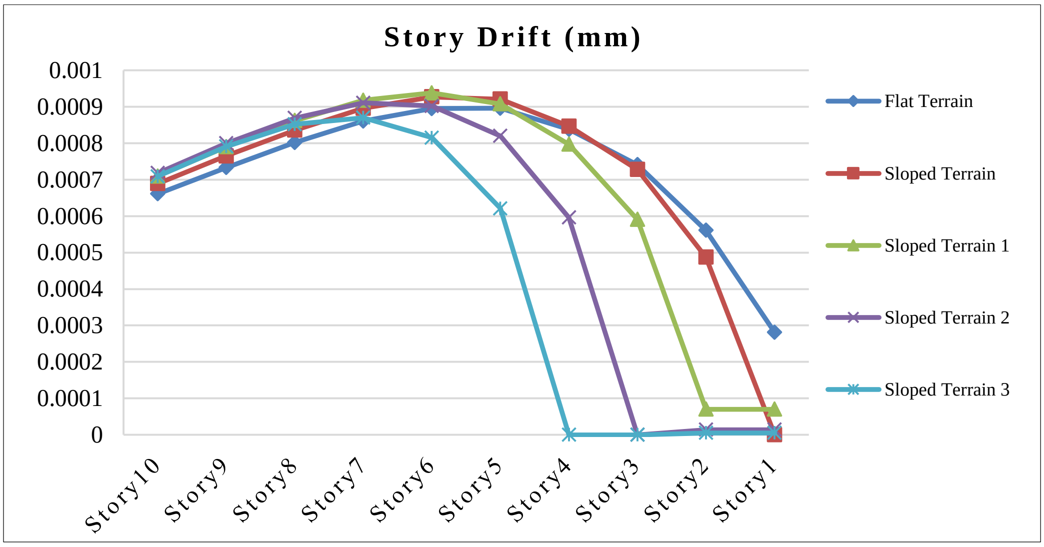


Figure 11. Story drift for models with different sloped terrain with shear walls and bracing systems

4.6. Story Stiffness of the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 12 to 15 presents the story drift of the different models for the flat terrain and different sloped terrain.

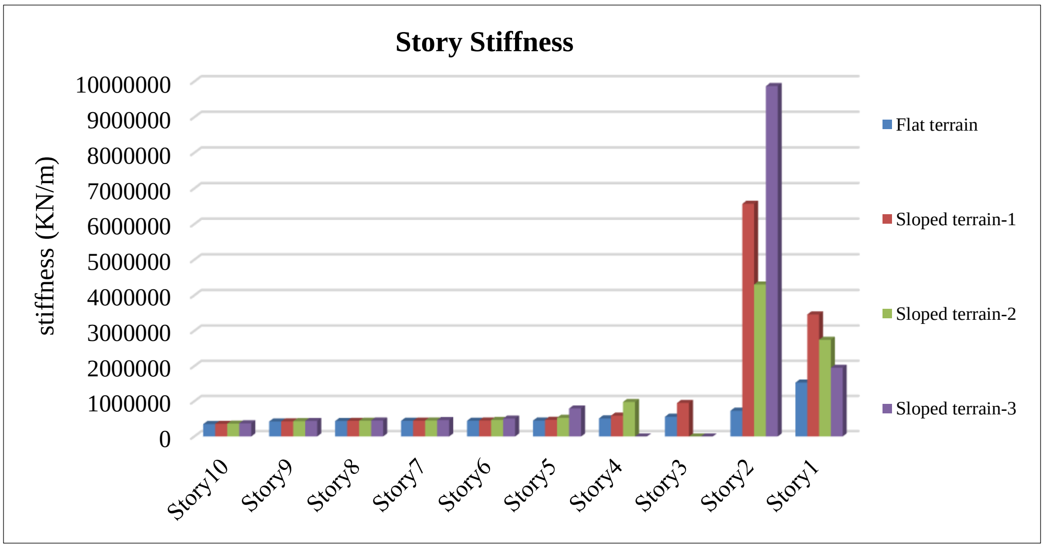


Figure 12. Story stiffness for models with different sloped terrain without strengthening systems

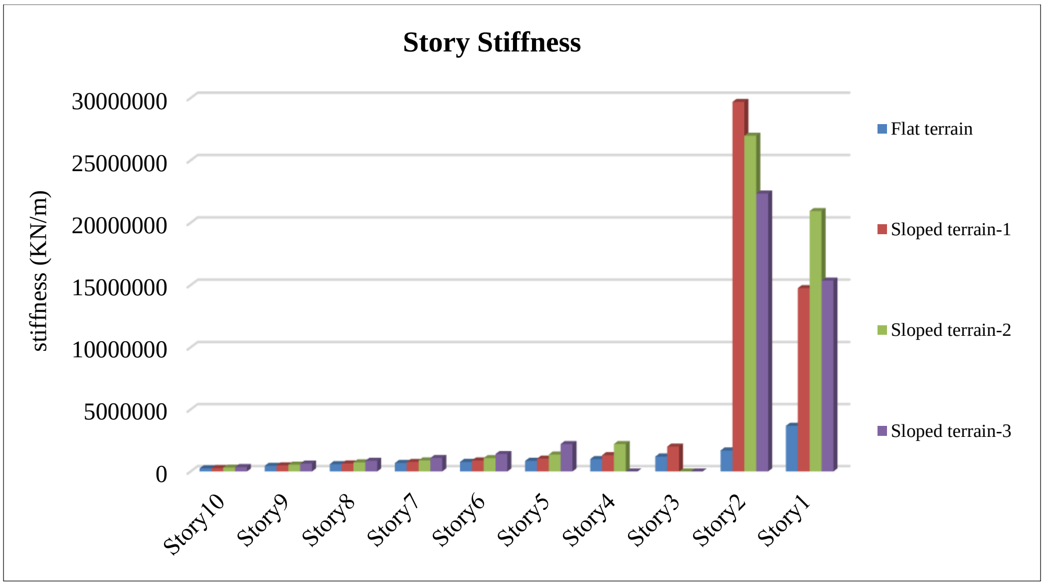


Figure 13. Story stiffness for models with different sloped terrain with shear walls systems

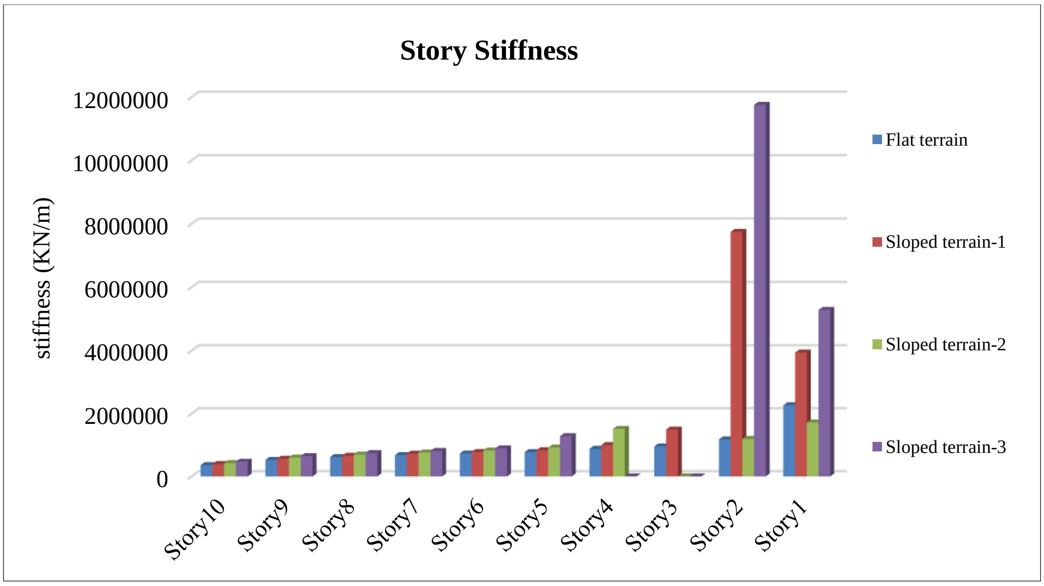


Figure 14. Story stiffness for models with different sloped terrain with Bracing systems

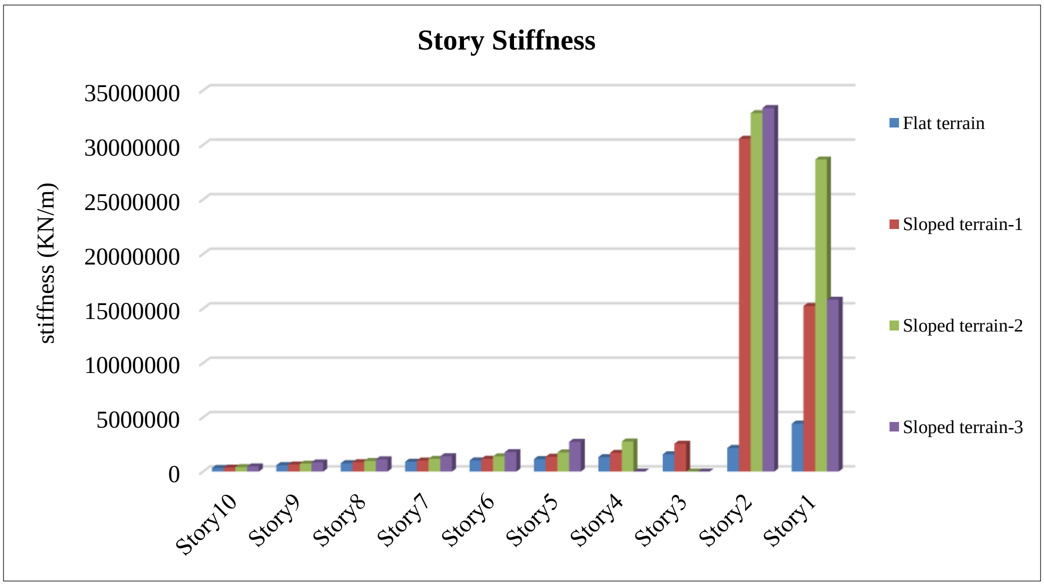


Figure 15. Story stiffness for models with different sloped terrain with shear walls and bracing systems

4.7. Base Shear for the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 16 to 19 presents the story drift of the different models for the flat terrain and different sloped terrain.

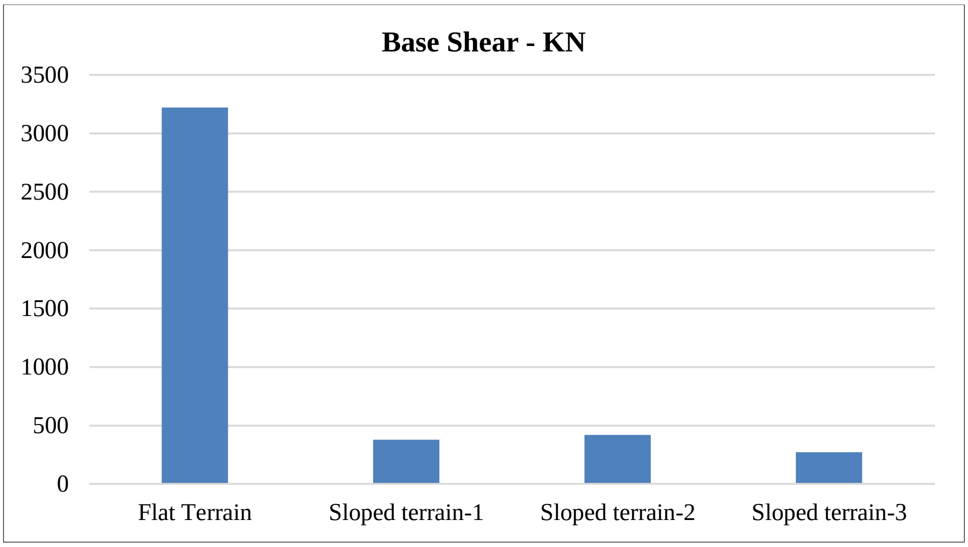


Figure 16. Base shear for models with different sloped terrain without strengthening systems

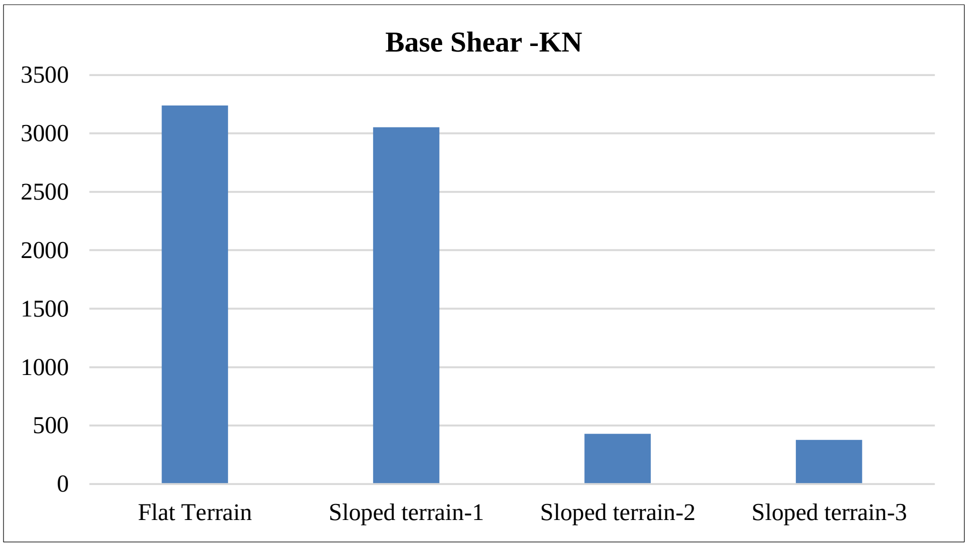


Figure 17. Base shear for models with different sloped terrain with shear walls systems

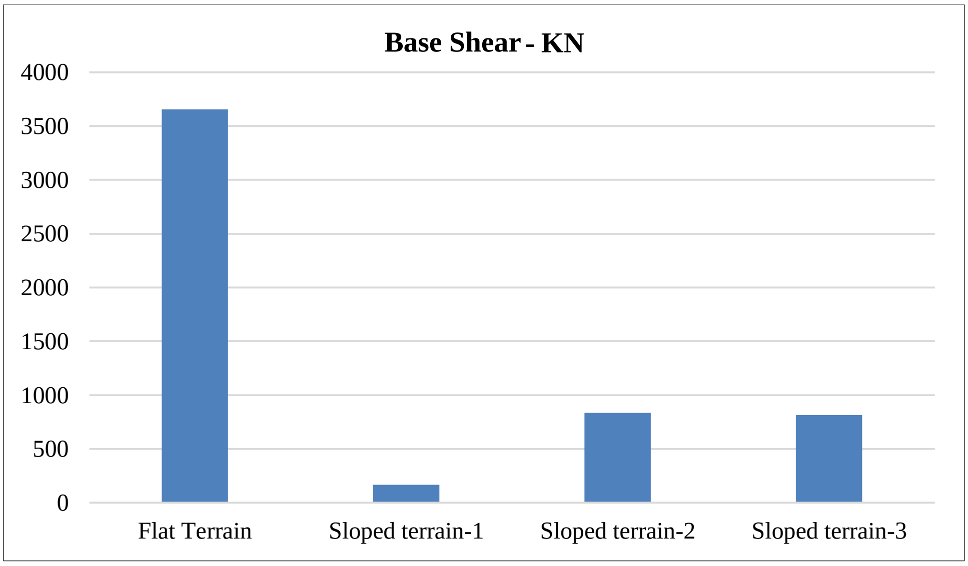


Figure 18. Base shear for models with different sloped terrain with Bracing systems

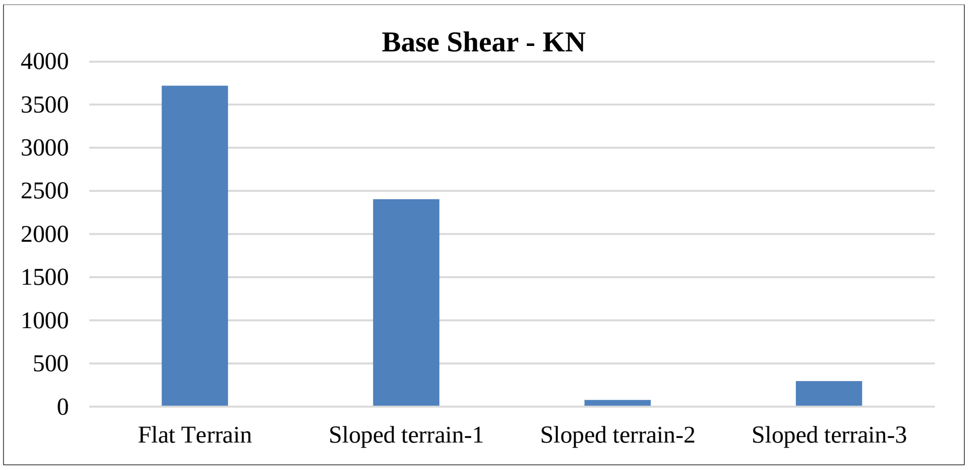


Figure 19. Base shear for models with different sloped terrain with shear walls and bracing systems

4.8. Column Shear Forces for the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 20 to 23 presents the story drift of the different models for the flat terrain and different sloped terrain.

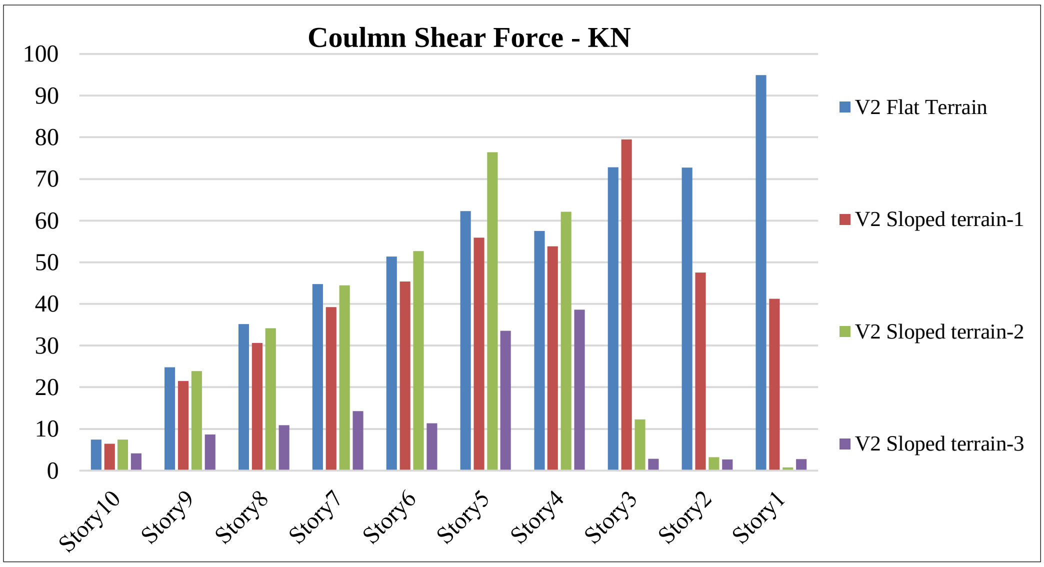


Figure 20. Column shear forces for models with different sloped terrain without strengthening systems

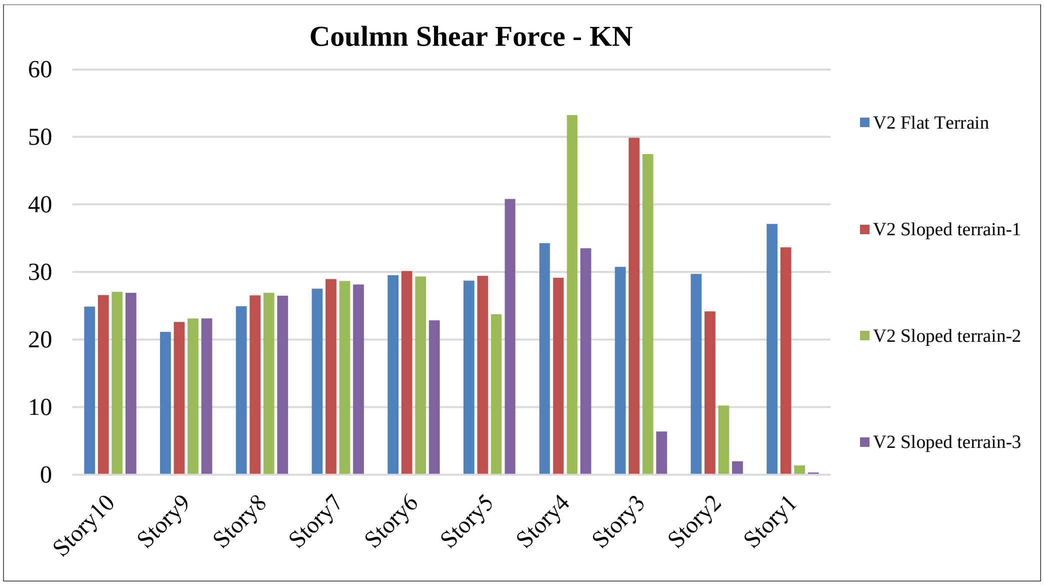


Figure 21. Column shear forces for models with different sloped terrain with shear wall systems

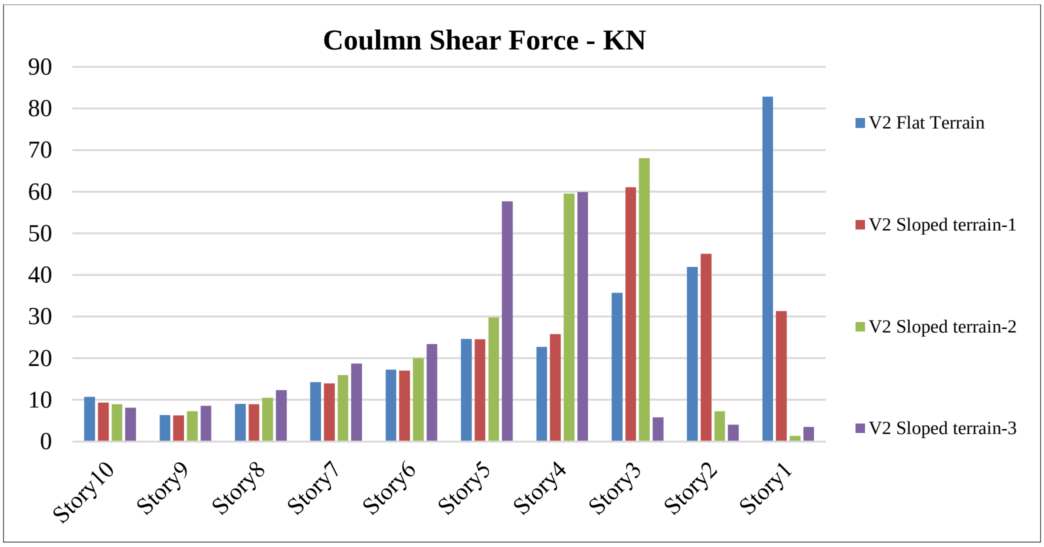


Figure 22. Column shear forces for models with different sloped terrain with Bracing systems

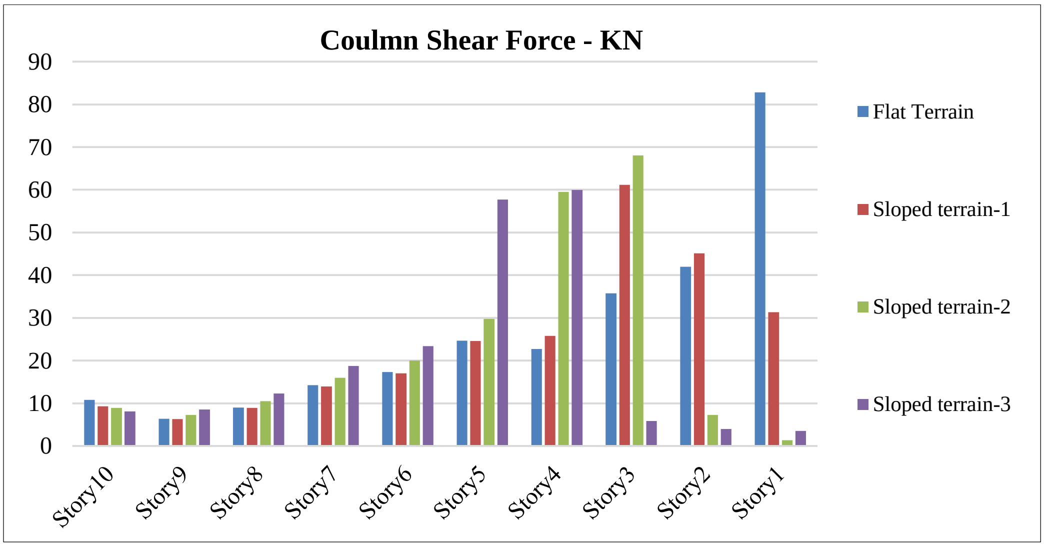


Figure 23. Column shear forces for models with different sloped terrain with shear walls and bracing systems

4.9. Fundamental Time Period for the Models on Flat and Different Sloped Terrain with Different Strengthening Systems

Figures 24 to 27 presents the story drift of the different models for the flat terrain and different sloped terrain.

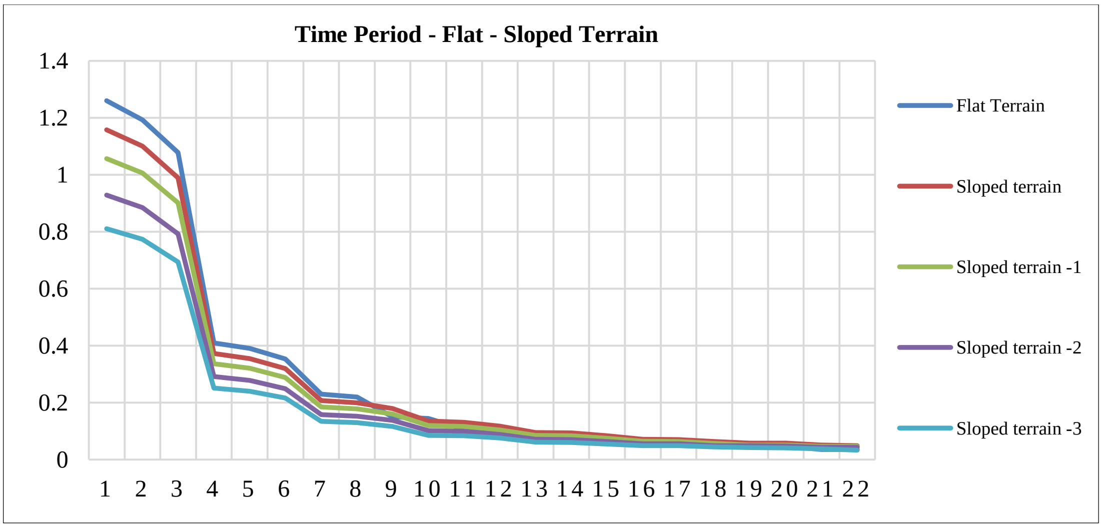


Figure 24. Fundamental time period for models with different sloped terrain without strengthening systems

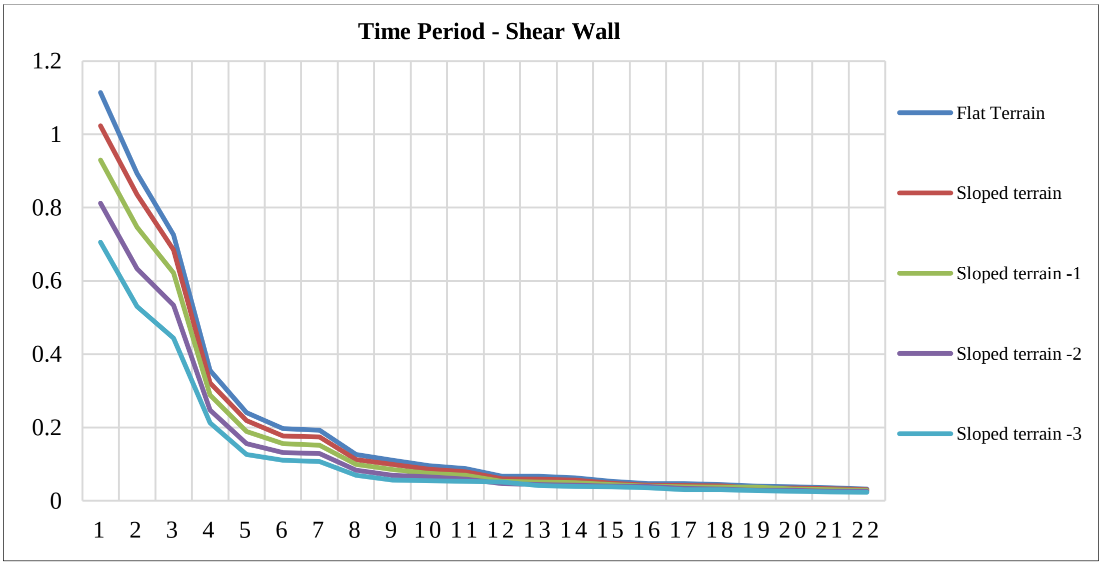


Figure 25. Fundamental time period for models with different sloped terrain with shear wall systems

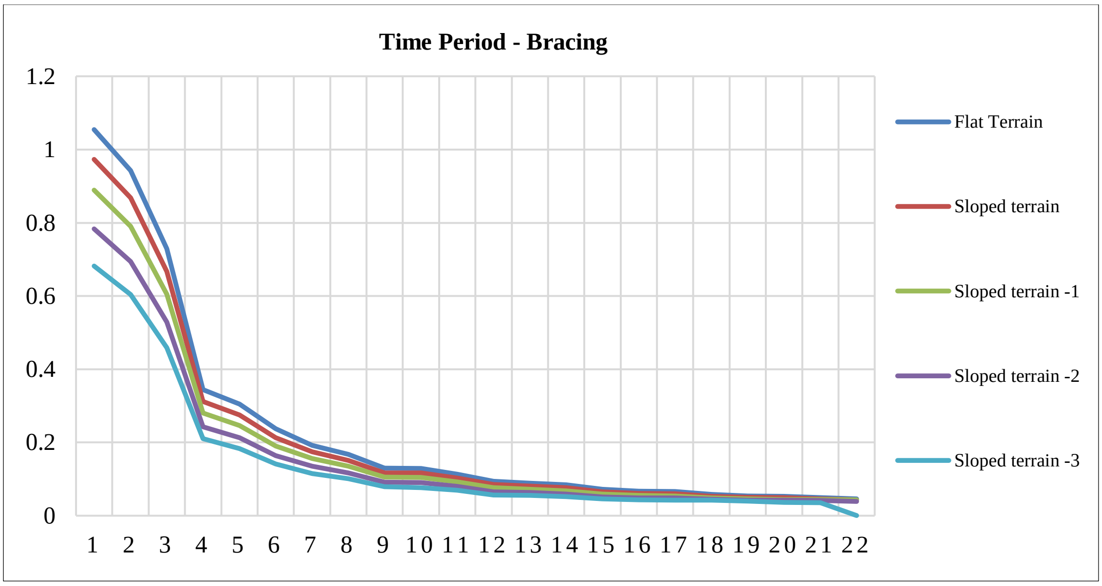


Figure 26. Fundamental time period for models with different sloped terrain with Bracing systems

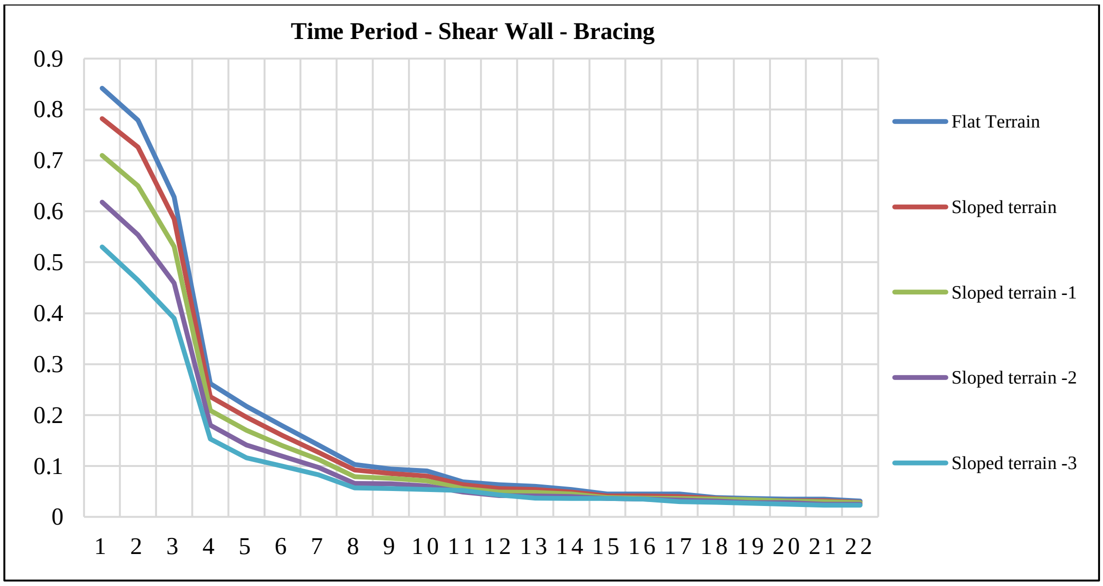


Figure 27. Fundamental time period for models with different sloped terrain with shear walls and bracing systems

5. Results

The results obtained from this study presented for the 3D-Models with different strengthening systems on different slopes. In the studied models, the seismic loads have been analyzed on different slopes. The obtained results from this study have been compared such as displacement, column shear, base shear, story drifts, fundamental time period and story stiffness.

5.1. Lateral Displacement

The seismic loads are considered a significant parameter when designing R.C. buildings, especially on sloped terrain. A research study presented the response of the building top stories displacements helps to understand the level of damage to the buildings. To avoid building excessive deformation during the design process of the building the drift and lateral deformation of the building should be carefully considered [29]. For the studied models, the structural and non-structural elements will have an excessive deformation in the R.C. buildings. Figure 28 presented the maximum displacement in the buildings on sloped terrain with different strengthening systems. It can be seen that adding the steel bracing or shear wall affected the maximum displacement of the model but adding the bracing and shear wall showed much effective control in the maximum displacement. Even on the sloped terrain and the torsional effect, the value of the maximum displacements decreases when compared with models without strengthening systems or in comparison to models with the shear wall or bracing systems alone.

The dynamic analysis parameters for the 3D-models' buildings on flat and sloped terrain with different strengthening systems and different slopes. The displacement of the model's top floors was found with a variation from 20.87 mm to 13.97 mm when using shear wall and bracing as a strengthening system with a reduction of 33.1%.

Figure 28 shows the result of the analysis of the models strengthened by different strengthening systems where the minimum displacement was for the model with shear wall and bracing systems. It is obvious that the bracing and shear wall together reduces the displacement in comparison to each system alone.

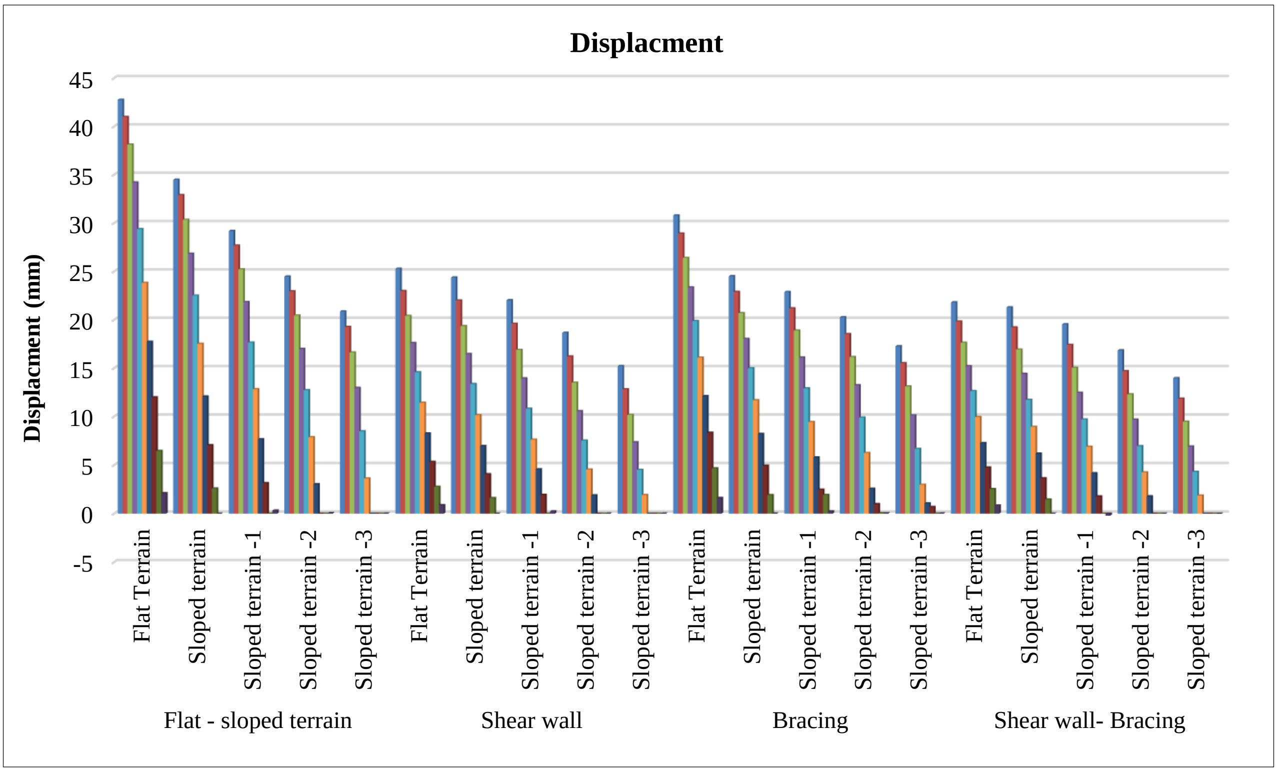


Figure 28. Displacement of 3D- models with and without strengthening systems

5.2. Story Drift

The story drift is considered an important parameter when examining the behaviors R.C building effectively. A research work studded the structural and nonstructural damage in comparison to the displacement the story drift is considered a reliable parameter [30].

The story drift for the building on sloped terrain with a bracing system, shear wall as well as shear wall and bracing systems were observed, and the graphs were plotted for the different cases shown in Figure 29.

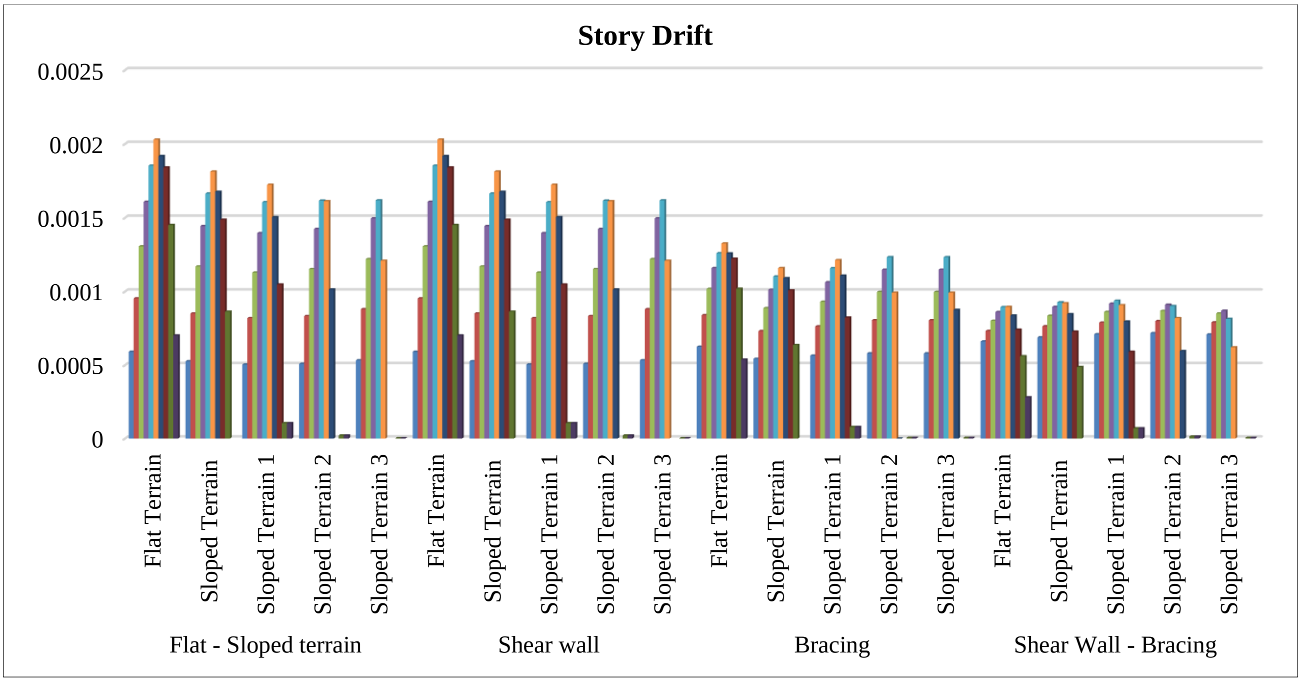


Figure 29. Story drift of 3D- models with and without strengthening systems

A significant difference in values in the story drift was observed between the models strengthened by shear walls and bracing and the models without strengthening and it is found that the story drift reduction varies from 20.64% to 41.84%. Moreover, it was observed that the strengthening systems induced less story drift at every level of the model's stories. Figures 29 shows the result of the analysis of the different models strengthened by different strengthening systems where the minimum story drift was for the model with shear wall and bracing systems. It is obvious that the bracing and shear wall together reduces the displacement of each system alone.

5.3. Story Stiffness

The story stiffness for the buildings depends mainly on the shape, size, and bracing or shear walls. Figure 30 represents the story stiffness of the stories of each model with and without strengthening systems. The story stiffness for the models with shear walls and bracing increased by 1.018 times than the model with bracing and it increased by 1.349 times with respect to the model with shear walls. It can be noticed clearly that adding shear walls and bracing to the models to resist the seismic loads increases the story stiffness of the RC. Buildings.

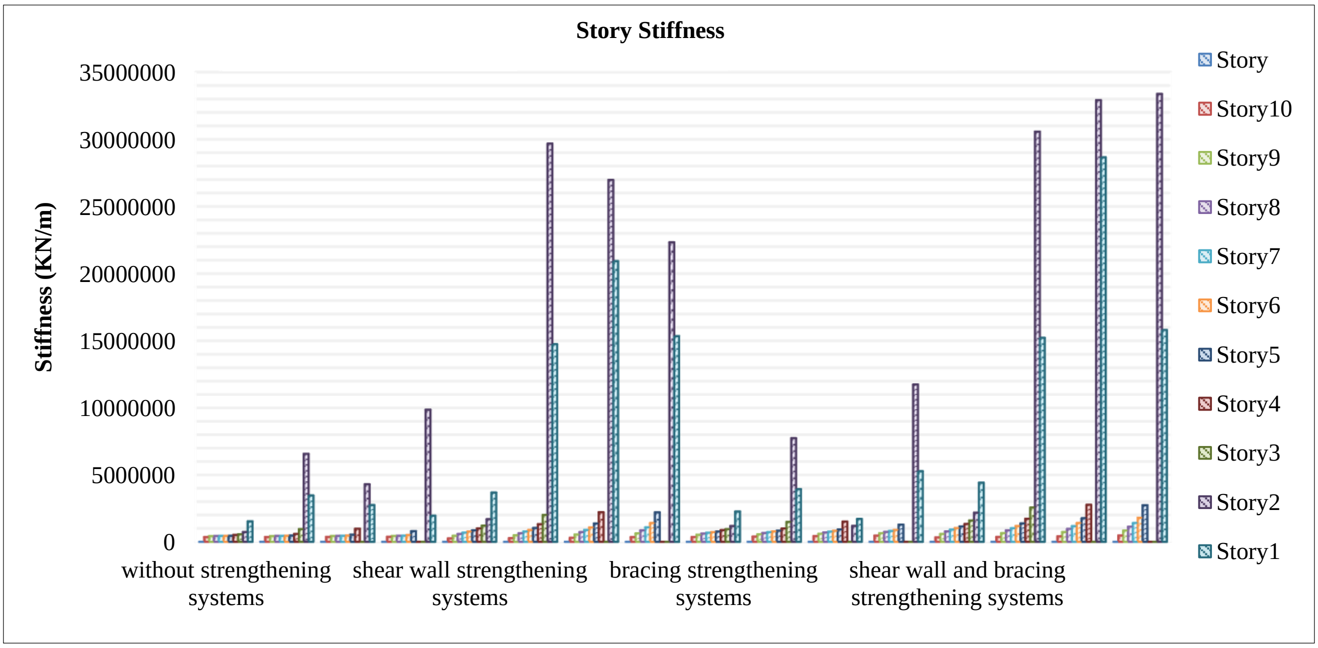


Figure 30. Story stiffness of 3D- models with and without strengthening systems

5.4. Columns Shear Forces

It has been observed that the use of shear wall and bracing as strengthening system results in inducing less shear force on the columns design shear forces. The reduction of the values at the different levels varies from 17.73% to 56.07%. however, the values for the results obtained from the analysis showed that the maximum shear forces for the models with strengthening systems is for the models with bracing systems and the values decreases for the system with shear wall and the minimum values are for the models strengthened with shear walls and bracing systems.

Figure 31 shows the result of the analysis of the different models strengthened by different strengthening systems where the minimum displacement obtained was for the model with shear wall and bracing systems. It is obvious that the bracing and shear wall together reduces the design shear forces than that of each system alone.

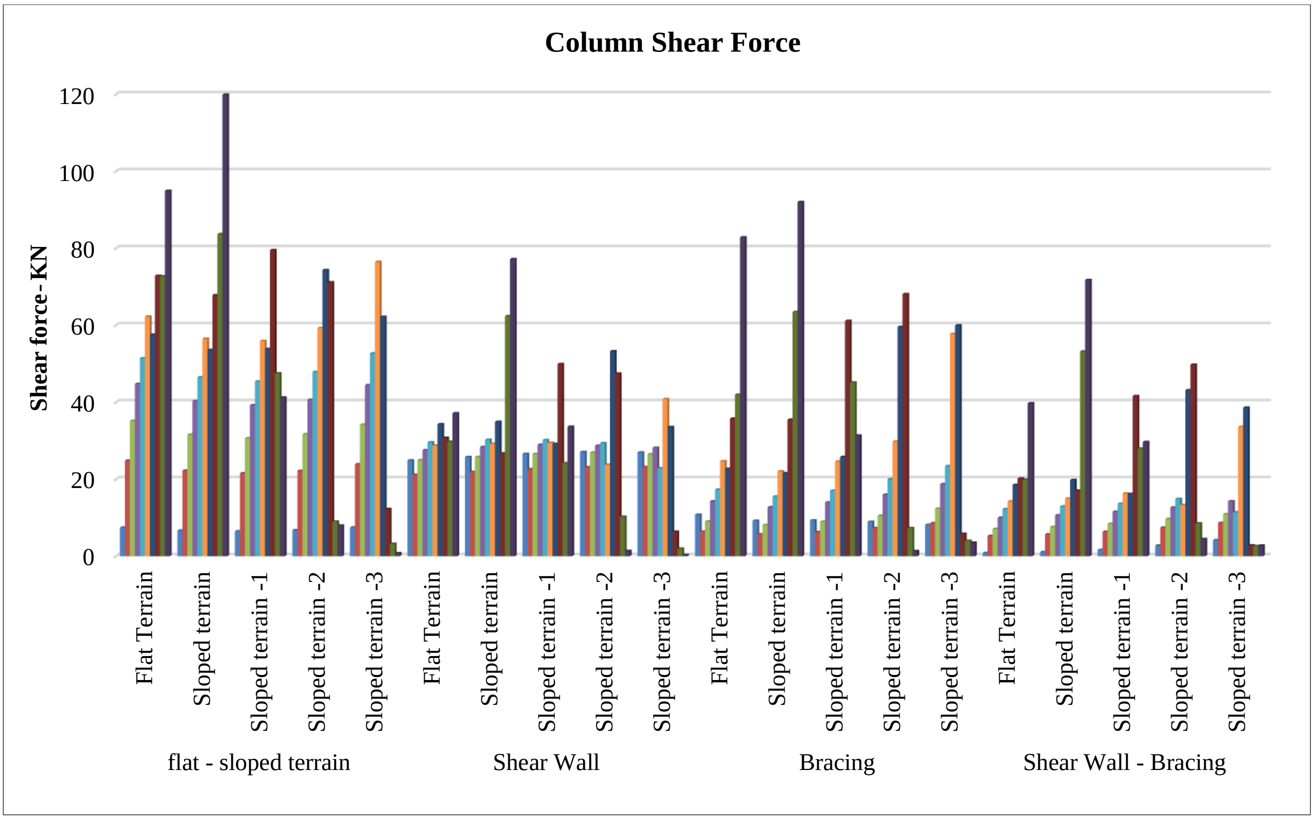


Figure 31. Columns shear forces of 3D- models with and without strengthening systems

5.5. Base Shear

The base shear is considered as the total lateral force at the structure s' base that is induced due to the seismic loads of the ground motions of the earthquake, which depends on the structure s' shape, fundamental time periods as well as the types of the soil at the construction sites. The base shear also depends on the structural seismic weight. For this study, different cases were analyzed where the first case the shear wall was used with the building structure, in the second case the X-bracing system was used with the building structure where it was applied in both directions, and in the third case the shear wall and bracing were applied in both dimensions on different sloped terrain. It was observed that the steel bracing systems only increase the base shear of the building more than the shear wall system and that values are decreased when using the shear wall and bracing system together.

It has been observed that the base shear is decreasing substantially with the use of strengthening systems with a value of about 21.19% but with the increase in the slope, the base shear decreases only by about 63.34% which is mainly for the reduction of model weight and columns at different levels.

Figure 32 shows the analysis results for the different models strengthened with different strengthening systems that showed an increase in the base shear with the shear wall and bracing systems.

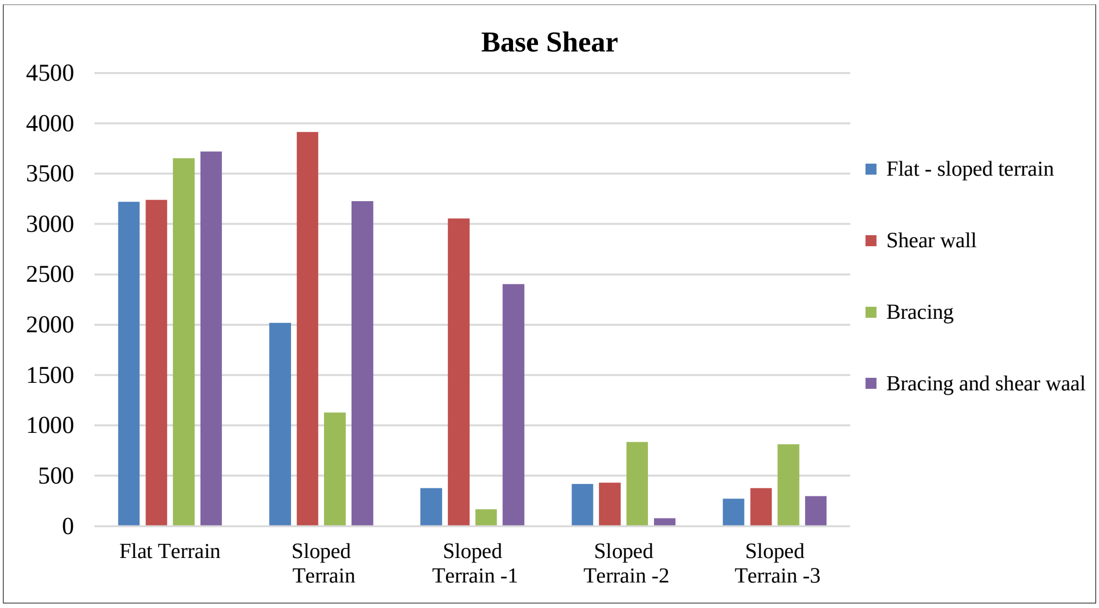


Figure 32. Base shear of 3D- models with and without strengthening systems

5.6. Fundamental Time Period

The seismic behavior of the R.C. buildings depend on the fundamental time period of the structures and the building base shear also depends on the building's natural time period. The fundamental time period of the building is normally calculated according to the codes using an empirical formula. However, the code formulas are only for the regular buildings, and the formula does not give an accurate fundamental time period for the buildings with braced and shear walls together [30, 31].

Figure 33 showed the fundamental time period variation for the building where it was clear that the use of shear wall and bracing systems for resisting the seismic loads decreases the fundamental time period however the base shear did increase with the bracing but decreases with bracing and shear wall systems.

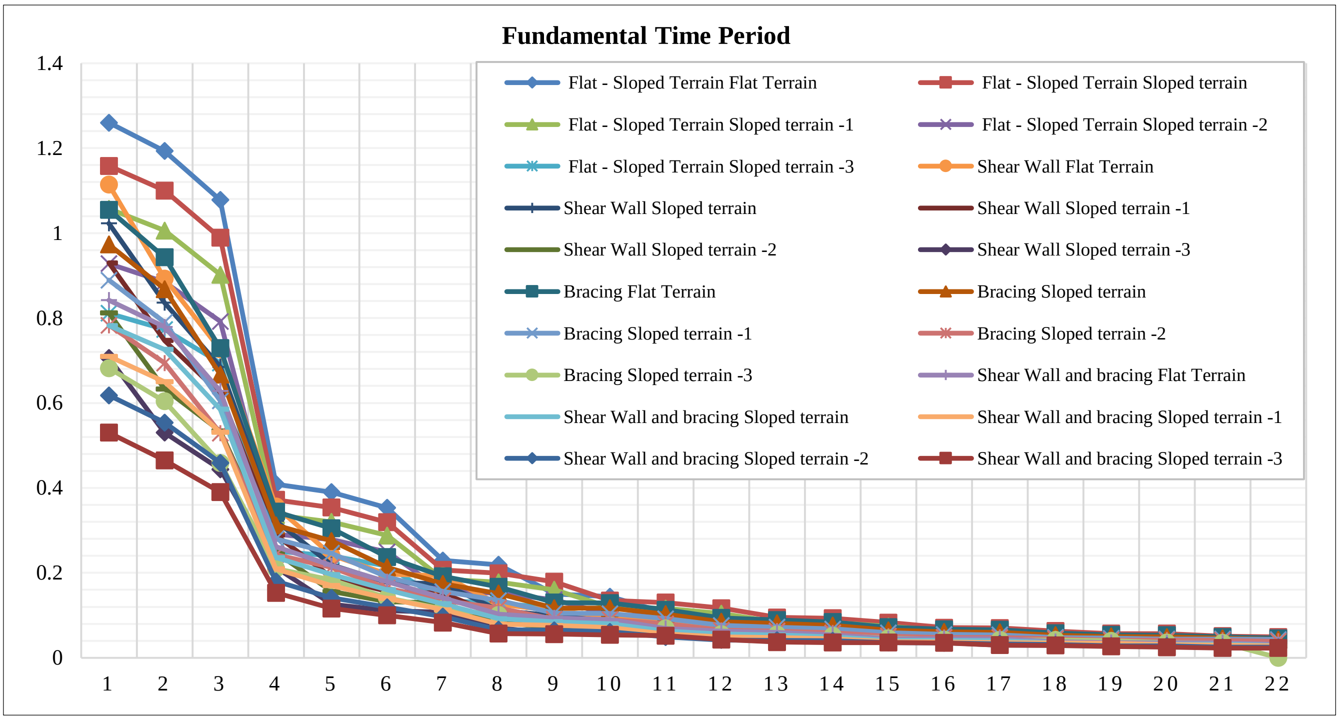


Figure 33. Fundamental time period for models with and without strengthening systems

The results of using the combined shear wall and bracing system compared with the use of shear wall or bracing system alone with respect to the different parameters presented in this work showed a great enhancement where the displacement of the models was decreased by 33.1% for the use of the combined strengthening system.

The same trend in the story drifts a significant enhancement was observed for the use of the combined strengthening system with a reduction in the drift values between 20.64% to 41.84% was observed at the different levels of the studied models in comparison to the models with shear wall or bracing systems as strengthening systems. In comparison, the models' story stiffness for the studied models with combined strengthening systems showed an increase in the stiffness that increased 1.018 times more than the models strengthened by bracing systems only and an increase of 1.349 times in comparison to the models with shear walls only, as the story stiffness for the buildings depends mainly on the shapes, sizes, and bracing or shear walls used for the models.

The column shear forces recorded a higher reduction value for the forces as the use of different strengthening systems reduces the column shear forces at the different levels. However, the results obtained from the analysis showed that the reduction values vary from 17.73 to 56.07% where the maximum values of the shear forces for the models using strengthening systems are for those with bracing systems, and these values decrease for the systems with shear walls. The minimum values are for the models strengthened with shear walls and bracing systems. Comparing the results of the base shear of the different models presented in this study showed that it has been observed that the base shear is decreasing substantially with the use of shear wall and bracing systems than the use of bracing systems by 21.19% and that percentage will be 63.34% when compared to the use of shear wall strengthening systems, which is mainly due to the reduction of model weight and columns at different levels.

The seismic behavior of the R.C. buildings depends on the fundamental time period of the structures, and the building's base shear also depends on the building's natural time period. Comparing the fundamental time period variation for the building for the use of different strengthening systems decreases the time period, form the studied models, it is clear that the use of shear wall and bracing systems for resisting the seismic loads decreases the fundamental time period in comparison to the use of bracing systems by 22.29% and this reduction value is 24.93% when using the shear walls. When comparing the reduction percentage to the models without strengthening systems, the reduction will be 71.9% in comparison to the use of shear wall and breaching as strengthening systems. However, the base shear did increase with the bracing but decreases with bracing and shear wall systems.

6. Conclusion

Buildings situated on sloped terrain in seismic load prone areas generally are irregular and unsymmetrical in both vertical and horizontal plans, hence it is susceptible to severe damage due to the seismic loads resulting from earthquake ground motions. The masses and stiffness of these buildings are varying along the horizontal and vertical plans, which means that the center of mass and the center of gravity of these buildings will not coincide together, and there will be a variation on the various floors' levels. Therefore, different strengthening systems have been used to increase the building stability and reduce the torsional effect of the building irregularity. The present work investigates the use of a combined shear wall and bracing strengthening system and compares the results with the different strengthening systems on sloped terrain and subjected to seismic loads. The investigation was conducted on a 10-story framed RC building on sloped terrain with different slopes subjected to seismic loads. A dynamic analysis and evaluation of the different types of strengthening systems and combined strengthening systems was performed to assess and compare the results of the lateral displacement, story drift, column shear forces, fundamental time period, base shear and story stiffness. Based on the obtained results, the following conclusions were found.

The use of the combined strengthening system investigated is found to be effective in the deduction of the lateral displacement. The joint displacement of a point was reduced from 24.48 mm for the frame configuration system and the value of the shear wall and bracing configuration system was 16.85 mm, which reduces the lateral displacement by 33.1%. For the story drift, the use of the shear wall and bracing system as a strengthening system reduces the drift of the stories by a percentage between 20.64 to 41.84% at the different story levels in comparison to the use of a shear wall or bracing system alone. The comparison of the story stiffness of the studied models with the different strengthening systems was investigated, and the stiffness of the buildings with shear walls and bracing showed an increase of the story stiffness of 1.018 with respect to models with bracing systems and 1.349 with respect to models with shear walls. Regarding the columns, shear forces were between 17.73 and 56.07%, where it can be seen that the frame forces were reduced by a considerable value with the use of the strengthening system. Among the strengthening systems used the base shear reduces by 21.19% in comparison to the shear walls and 63.34 % in comparison to the bracing strengthening system. The fundamental time period of the models studied showed that the use of the strengthening system proposed reduces the time period for the models with bracing systems by 22.29% and by 24.93% for the models strengthened by shear wall. The strengthening systems are effective in reducing the different studied parameters. However, the most effective system is the use of the shear wall and bracing in comparison to any other system.

7. Declarations

7.1. Data Availability Statement

The data presented in this study are available in the article.

7.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

7.3. Conflicts of Interest

The author declares no conflict of interest.

8. References

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