RESEARCH ARTICLE **ISSN 2738-9898 (Print) ISSN 2738-9901 (Online)**

Comparative Study on Seismic Behavior of Regular and Irregular Building in Sloping Ground

Prakash Poudel and Badri Adhikari*

School of Engineering, Pokhara University, Pokhara, Nepal

* Author to whom correspondence should be addressed; E-Mail: *badriadhikari@pu.edu.np*

Received: 18 November, 2024; Received in revised form: 08 December 2024; Accepted: 29 December, 2024; Published: 31 January, 2025

Abstract

Nepal is situated in a highly earthquake-prone region. Majority of land is covered by hilly and mountainous topography. Due to the scarcity of plain ground, urbanization has rapidly increased with the construction of buildings on sloping ground. These buildings constructed in sloping ground are susceptible to severe damage due to earthquake. The aim of this study is to compare seismic behavior of different configuration of building built in hill slope: step back (SB), step back set back (SBSB), split foundation (SF), split foundation set back (SFSB) buildings having regular and irregular shape considering soil effect (SSI) and compared with the fixed base and with the building constructed in Plain ground (PG). To fulfill this aim selection of 20 distinct models, with 10 adhering to regular shapes and the remaining 10 exhibiting irregular configurations. Moreover, half of the models incorporate fixed bases, while the other half considers the impact of soil. All models maintain consistent material properties and other parameters. The natural slope of the ground for structures on sloping terrain is set at 30^0. Stiffness of soil is assigned as a point spring to the base of structure for introducing effect of soil. The building models are constructed using Finite Element Analysis (FEM) software, specifically ETABS version 16.2.1 and the non-linear time history analysis is done by using Gorkha earthquake, Empirical earthquake and Turkey earthquake time history function. NBC 105:2020 code is used for this seismic analysis. Finally the seismic performance of all the buildings is evaluated by determining fundamental time period, base shear, top story displacement, inter story drift and torsional irregularity ratio by the use of FEM software ETABS and these values were compared with different building configuration and the configuration more susceptible and less susceptible to earthquake is determined. The study concludes that on sloping ground SF is found to be more vulnerable while SBSB building performs better than other building. The incorporation of soil effect has substantial impact on building performance and due to flexibility induced in base the top displacement and time period of flexible base structure has increased while the base shear is decreased by considering soil effect.

Keywords

Seismic, Regular and Irregular Building, Sloping ground, SSI

1. **Introduction**

1.1 Background of Study

Construction of Buildings in hill areas is rapidly increasing in last few decades, especially in areas prone to earthquake. Sloping ground conditions complicate the seismic behavior of structures. Due to scarcity of plain ground structures are built in sloping ground whichpossess structural and construction problems. It is preferable that construction, especially residential development, follow the natural ground slope [1]. As the building built in hilly areas are more vulnerable due to presence of mass irregularities, stiffness irregularities and geometric irregularities [2],[3]. Due to their unsymmetrical nature, structures built on hill slopes exhibit distinct structural behavior than those built on flat ground. These structures are more attracted to shear forces and torsional moments [4]. The construction of infrastructure in hilly areas is the major challenge due to aesthetic and shortage of land and higher cost of land the buildings with step back and set back configuration are accepted[5],[6],[7].These buildings located in slopes has the worst seismic performance [2],[8]. The cumulated damage is strongly impacted by the ground motion of the structure and causes fatigue failure under earthquake [9].In countries like Nepal and India low magnitude earthquake can also cause severe damage of the structure [10]. Stepped building construction is widely increasing in modern urbanization [11]. The changes in terrain cause significant changes in stiffness of hill buildings [12]. Sloping terrain significantly increases the seismic response of 10 to 15-story buildings [13].The interaction between the irregularity of buildings and dynamic response induced by earthquakes in sloping ground can significantly affect their structural performance and vulnerability. Buildings on sloping grounds may have inferior seismic performance due to damage from past earthquakes [8]. Buildings with step back configuration, step-back set back configuration, split foundation and split foundation setback are normally constructed in sloping ground. These are frequently built as a result of plain land's limitations and high cost to level the ground [14]. About 68% of Nepal’s total area is covered by hilly region and 15% of area is covered by mountainous region [15], where construction of building in sloping topography is common in this region. These areas are more prone to seismic activity.

The term "soil structure interaction" describes how a structure reacts to the impact of the soil and how the soil reacts to the motion of an existing structure. Anywhere on the surface where a structure is built, the free field ground motion is impeded, leading to various interactions between the building and the soil. The intensity and distribution of seismic vulnerabilities can be altered by taking into account soil structure interaction (SSI) [16]. Structural response is impacted when a structure experiences seismic excitation because it interferes with soil [17]. The response of structure is influenced by structure itself its foundation and underlying soil. This interaction is essential factor that complements the structure’s dynamic characteristics [18]. The fixed base assumption does not accurately describe the seismic behavior of buildings situated on soils [19]. So, the effect of SSI should be addressed during modelling. When this aspect is considered, the structure provides much more accurate results compared to when it is not considered [20].This work focuses on the seismic behavior of regular and irregular structure in sloping ground when effect of SSI is considered and compare it with the result obtained while not considering effect of soil. Figure 1 shows typical buildings constructed in slope of hilly areas of different cities of Nepal.

a) Location: Badkhola, Syangja

b) Location : Sarangkot, Kaski

c) Location : Sundari Danda, Kaski

d) Location: Putalibazar, Syangja

Figure 1: Typical buildings constructed in slope of hilly areas of different cities of Nepal

Figure 2a shows the SDOF structure of mass ‘m’ and stiffness ‘k’ resting on a fixed based where deflection is caused by the static force ‘F’ such that

$$F = K\Delta \quad (1)$$

Also in the figure 2b, it represents the MDOF structural system resting on flexible bases, where springs are used to account for its translational and rotational stiffness.

Slope stability refers to the condition in which an inclined terrain can sustain its own weight and withstand external forces without undergoing any displacement [22]. When the required stability criteria is not met, the soil or rock mass on slope may experience downward movement, which can occur gradually or rapidly. The phenomena are generallyreferred to as slope failure. The shear strength of the soil, which is commonly described as the friction angle (ϕ) and cohesion (c), determines the slope's stability. Failure may occur due to the translation of the slope, rotation of the slope, or a combination of both. Geotechnical design requires evaluating the stability of the soil [23]. Figure 3 illustrates shallow, intermediate, and deep failures, as well as multi-slip failure.

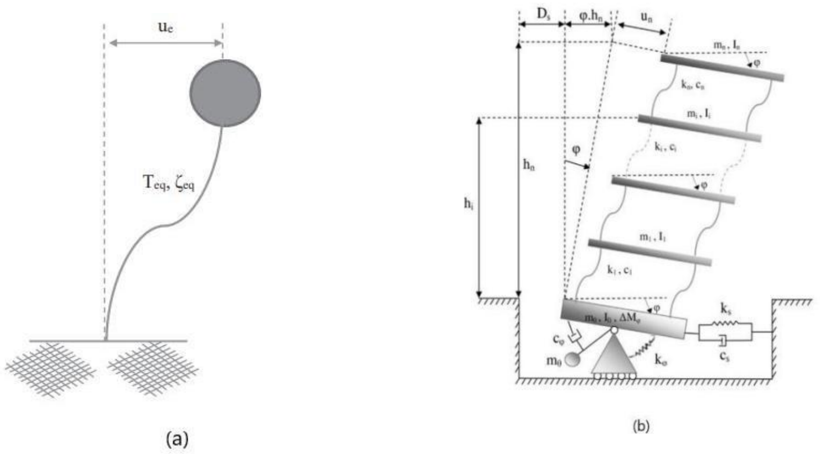


Figure 2 : (a) Equivalent SDOF fixed –base system (b) Non-linear soil-MDOF structure system [21]

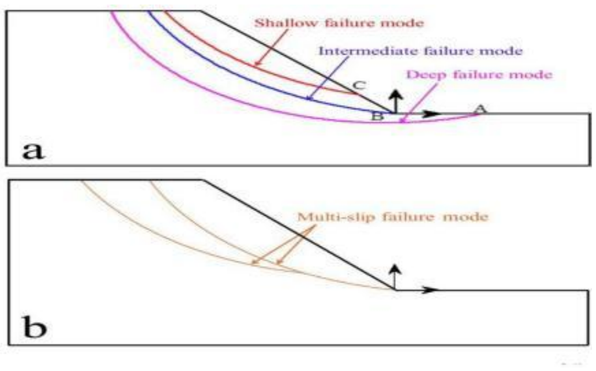


Figure 3: (a) Shallow, intermediate and deep failure (b) Multi slip failure [24]

In these circumstances, analyzing the equilibrium state when incipient failure is advanced and comparing the strength required to preserve limiting equilibrium with the available strength of soil will yield a quantitative estimate of the factor of safety (FOS) [25]. The ratio of the soil's available shear strength to the amount needed to maintain equilibrium is known as the factor of safety [26].

Despite the extensive research conducted on seismic behavior of building and the impact of irregularity on their structural performance, there are not many thorough studies that are explicitly concerned with the comparison of regular and irregular structure in sloping ground situations considering soil effect. By investigating the dynamic response, inter story drifts, fundamental time period, displacements and forces of these structures, we can identify the differences in their behavior and assess their relative vulnerability.

The main objective of this study was to conduct a detailed comparative study on the structural responses of regular and irregular structures under various types of loads on sloping ground. This study aims to determine the safest building configuration among the possible configurations that can be constructed on hill slopes, and to investigate the effects of irregularities and soil effects, including step-back, step-back set-back, split foundation, and split foundation set-back, while comparing the results with regular and plain ground configurations building. The study concentrates on a specific geographical area with a significant history of seismic activity and buildings constructed on sloping terrain. Various building types, including residential, commercial, and institutional structures, are included in the analysis to represent the construction practices prevalent in the selected region. The study focuses on examining building components, including setbacks, step-backs, and split foundations, to understand how irregularity affects the seismic performance of buildings. The nonlinear time history analysis has been conducted using FEM software ETABS v16.2.1. The models used in this study involve simplifications and assumptions that may not precisely replicate real-world buildings, leading to potential discrepancies between the behaviors observed in numerical simulations and the actual performance of real buildings under seismic conditions, and the impact of infill walls is not considered during the analysis.

2. Methodology

2.1 General framework

Methodology deals with general framework that is mainly used for the study, criteria that are required for analysis, design, and evaluation of responses, using both the code provisions (IS, NBC) and FEM and other structural programming software.

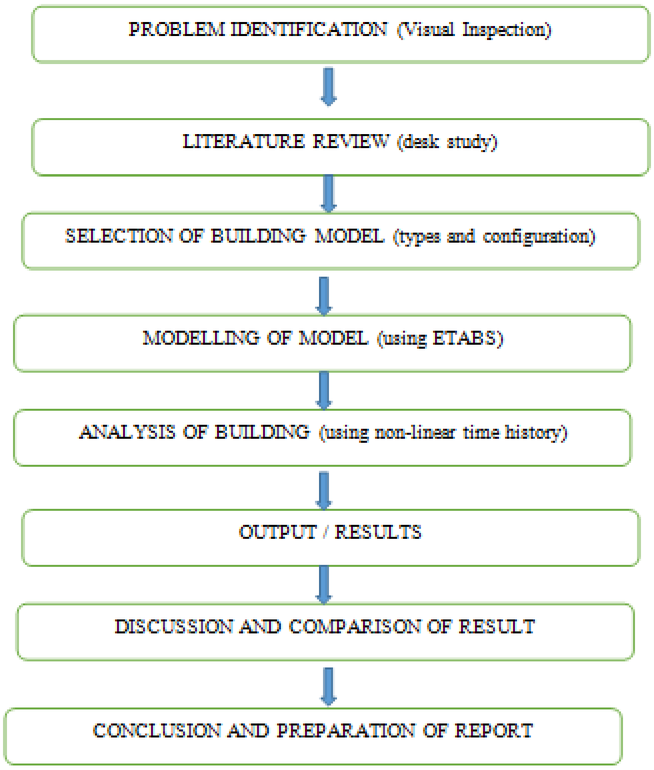


Figure 4: Flowchart of methodology for the study

2.2 Selection of Building

For this study, 20 different models were selected, evenly divided into 10 regular-shaped and 10 irregular-shaped structures. Among these, 10 models have a fixed base, while the other 10 incorporate the effects of soil. To ensure an accurate comparison, all models share identical material and section properties. Additionally, for models situated on sloping ground, a natural slope angle of 30° is considered [2]. Table 1 shows type and configuration of selected buildings for this study.

Table 1: Type and configuration of selected buildings

Base condition	Building Type	Building configuration	Notation
Fixed- base	Regular	Step back	SB-R
		Step back setback	SBSB-R
		Split foundation	SF-R
		Split foundation set back	SFSB-R
		Plain ground	PG-R
	Irregular	Step back	SB-IR
		Step back setback	SBSB-IR
		Split foundation	SF-IR
		split foundation set back	SFSB-IR
		Plain ground	PG-IR
Flexible- base	Regular	Step back	SB-R
		Step back setback	SBSB-R
		Split foundation	SF-R
		split foundation set back	SFSB-R
		Plain ground	PG-R
	Irregular	Step back	SB-IR
		Step back setback	SBSB-IR
		Split foundation	SF-IR
		Split foundation set back	SFSB-IR
		Plain ground	PG-IR

2.3 Details Soil and Slope Stability Analysis

The way the structure reacts was determined by how it interacts with the foundation soil. The interaction between the soil and the foundation depends on the foundation's size and elastic qualities. By substituting a flexible base for the building's fixed base using equivalent springs, the interaction between the earth and the structure is explored. The foundation soil is modeled using the values of the spring constant calculated as per the equation of Wolf as shown in Table 2 and Table 3 Shown values of spring constant for isolated footing which is calculated by using wolf equation for calculating spring constant [27].

Table 2: Equation for calculating spring constants given by wolf [27]

Spring Constants	Equivalent Radius
$Kx = \frac{32(1-v)GRo}{7-8v}$	$Ro = \frac{Af}{\sqrt{\Pi}}$
$Ky = \frac{32(1-v)GRo}{7-8v}$	$Ro = \frac{Af}{\sqrt{\Pi}}$
$Kz = \frac{4GRo}{1-v}$	$Ro = \frac{Af}{\sqrt{\Pi}}$
$KRx = \frac{8GRo^2}{3(1-v)}$	$Ro = \sqrt[4]{\frac{4Iyf}{\Pi}}$
$KRy = \frac{8GRo^2}{3(1-v)}$	$Ro = \sqrt[4]{\frac{4Iyf}{\Pi}}$
$KRz = \frac{16GRo^2}{3}$	$Ro = \sqrt[4]{\frac{2(Ixf+Iyf)}{\Pi}}$

Where, G is the shear modulus of the soil, υ is the Poisson's ratio of the soil, A_f is the area of the footing, R_o is the equivalent radius, I_{xf} is the moment of inertia of the footing about the X-axis, and I_{yf} is the moment of inertia of the footing about the Y-axis.

Table 3: Values of spring constant for isolated footing

Shear modulus (G) KN/m^2	Poisson's ratio (v)	K_x (KN/m)	K_y (KN/m)	K_z (KN/)	K_{rx} KN-m /rad	K_{ry} KN-m /rad	K_{rz} KN-m /rad
5300	0.3	91029.3	91029.3	106820	58671.7	58671.7	82140.3

2.4 Modeling of Buildings

The buildings are modeled using the FEM software ETABS version 16.2.1, which features 3D modeling and visualization tools, linear and nonlinear analytical capacity, comprehensive design capabilities for a range of materials, graphic presentations, reports, and schematic drawings that allow users to rapidly and simply grasp analysis and design findings. Table 4 presents the geometrical, material, and seismic properties of a selected regular and irregular building, highlighting key structural and architectural features, seismic considerations, and material specifications.

Table 4: Geometrical, material and seismic properties of selected regular and irregular buildings

Category	Regular Building	Irregular Building
Building Type	Residential Building	Residential Building
Structure Type	Moment Resisting Concrete Frame	Moment Resisting Concrete Frame
Column Section	350mm × 350mm	350mm × 350mm
Beam Section	300mm × 450mm	300mm × 450mm
Tie Beam Section	250mm × 300mm	250mm × 300mm
Shear Wall Thickness	230mm	230mm
Height of Building	21m	21m
Number of Stories	6 Nos	6 Nos
Slab Thickness	125mm	125mm
Bay in X-Direction	4 bays @ 6m c-c span	4 bays @ 6m c-c span
Bay in Y-Direction	4 bays @ 5m c-c span	6 bays @ 5m c-c span
Building Dimensions	24m × 20m	24m × 30m
Seismic Zoning Factor	0.3	0.3
Importance Factor	1	1
Soil Type	B	B
Location of Building	Pokhara	Pokhara
Concrete Grade	M20	M20
Steel Grade	HYSD 500	HYSD 500
RCC Unit Weight	24.99 KN/m^3	24.99 KN/m^3

Figure 5 illustrates the building model developed for the study.

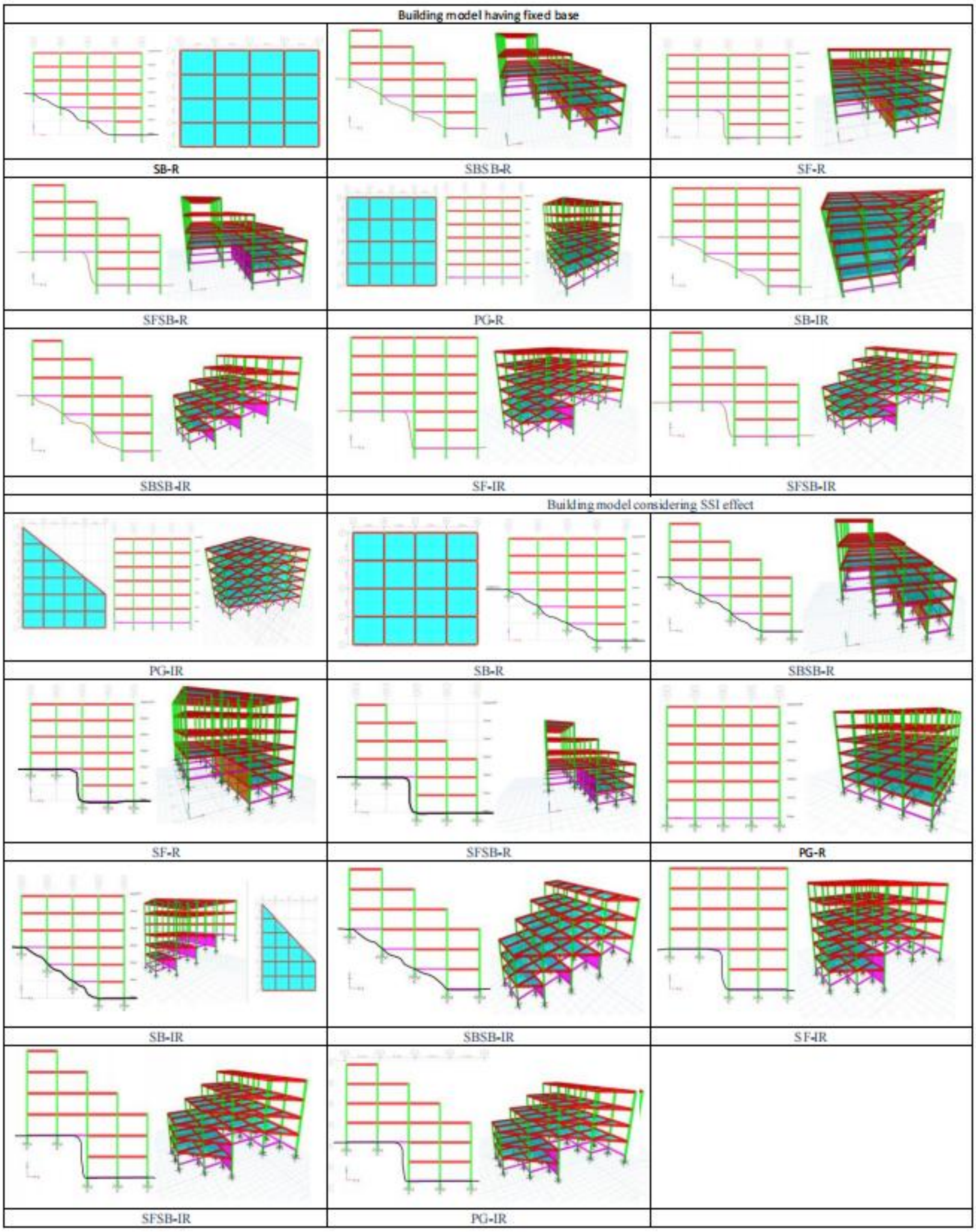


Figure 5: Building model

2.5 Analysis of building models

The selected models in this study depict moment-resistant buildings located in the seismic-prone Pokhara zone, featuring soil with classification type-B and designed in accordance with the important factor 1 specifications outlined in the NBC105:2020 code. The analysis adheres to the guidelines of NBC105:2020, IS 1893:2016 (part 1) and IS 456:2000. The dead load is determined as per IS 875-Part 1, while the live load is considered from IS 875-Part 2. The analytical approach employed involves nonlinear time history analysis, utilizing diverse time history data corresponding to selected seismic events, to comprehensively evaluate the seismic response of the structures.

2.5.1 Time history analysis

Time history analysis is performed to ascertain a structure's dynamic response to any loading. A single execution of ETABS can complete multiple linear time history instances. The history approach is based on the principles of earthquake structural dynamics and is carried out in accordance with relevant ground motion. It provides an evaluation of the dynamic structural response to loads, which can be linear or nonlinear depending on the selected time function. To solve the dynamic equilibrium equations K u(t) + C d/dt u(t) + M d2/dt u(t) = r(t),one of two approaches is used: modal or direct integration.

2.5.2 Linear time history analysis

The application employs the standard mode superposition approach of response analysis to solve the full structure's dynamic equilibrium equations of motion. Alternatively, the direct integration method directly integrates the entire equations of motion. While modal superposition is often more precise and efficient, the response obtained from direct integration is considered superior.

2.5.3 Non- linear time history analysis

The nonlinear modal time-history analysis method used in ETABS extends the Fast Nonlinear Analysis (FNA) method, which is designed for structural systems that are primarily linear elastic with a few predetermined nonlinear features. Nonlinear direct integration offers similar costs and benefits to those of a linear process, but unlike modal superposition, its results are highly sensitive to the size of the time step. The FNA method is superior to traditional time-stepping techniques in terms of speed, damping control, and higher mode effects, and it achieves exceptional accuracy when used with the appropriate Ritz vector modes.

Table 5 provides the time history data of the selected earthquakes, while Figures 6, 7, and 8 depict the time history graphs for the Gorkha Earthquake, Imperial Valley Earthquake, and Turkey Earthquake, respectively, highlighting the seismic response in both the X and Y directions.

Table 5: Time history data of selected earthquake

Earthquake	Location	Date	Magnitude (Ritcher Scale)	P.G.A, g
Gorkha	Nepal, Gorkha	25/04/2015	7.8	0.16
Imperial valley	USA, California	15/10/1979	6.95	0.28
Turkey	Kahramanmaras, turkey	6/2/2023	7.4	0.59

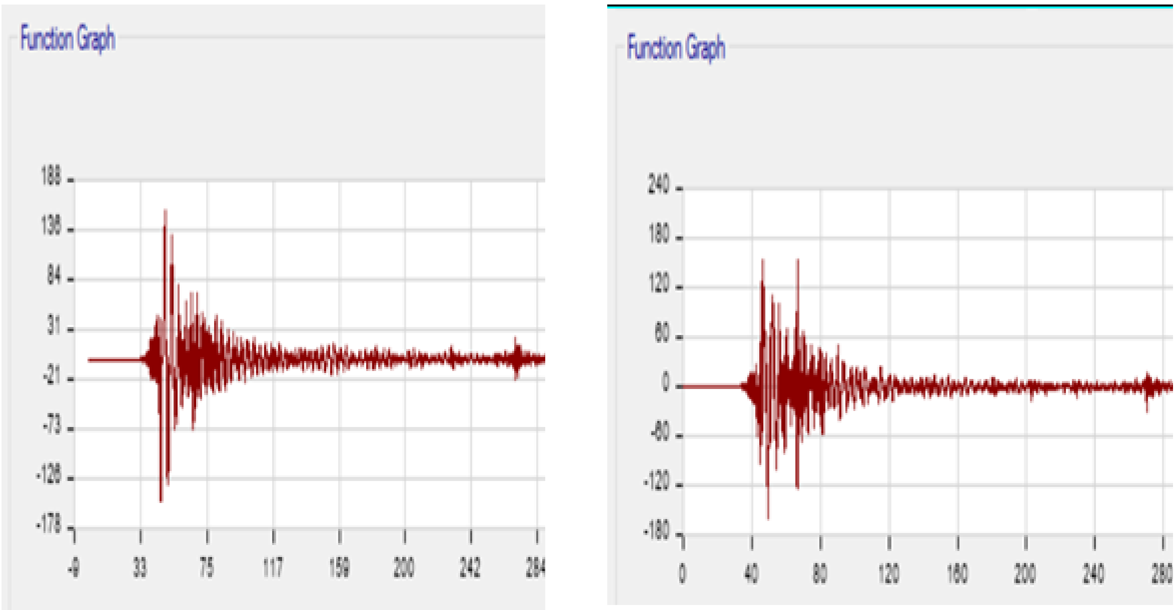


Figure 6: Time history graph of Gorkha Earthquake, along X-direction and along Y-direction

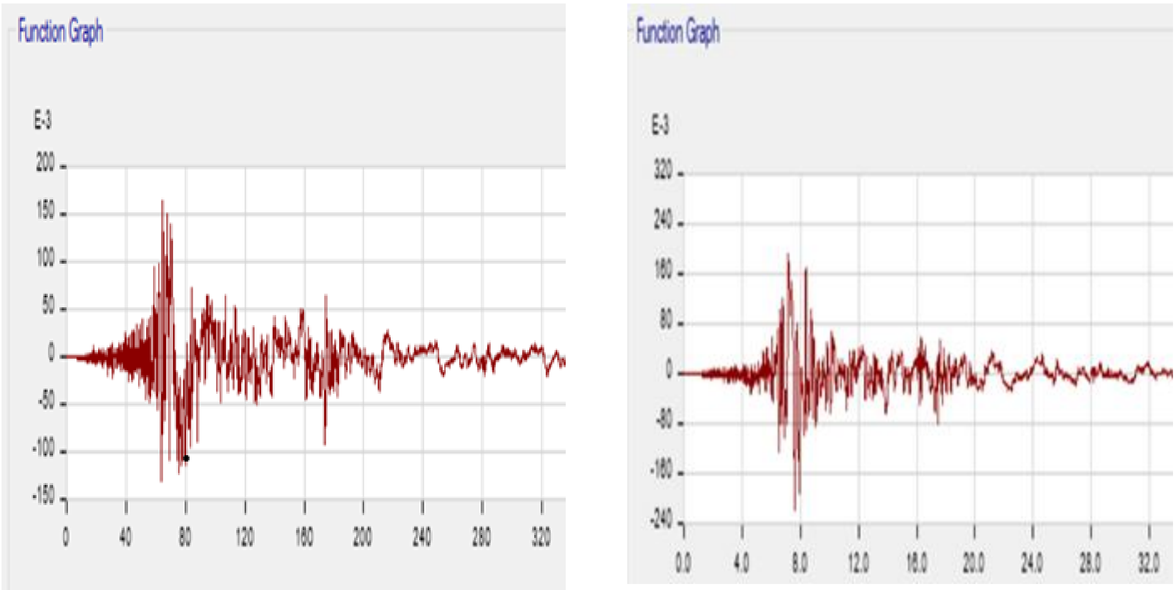
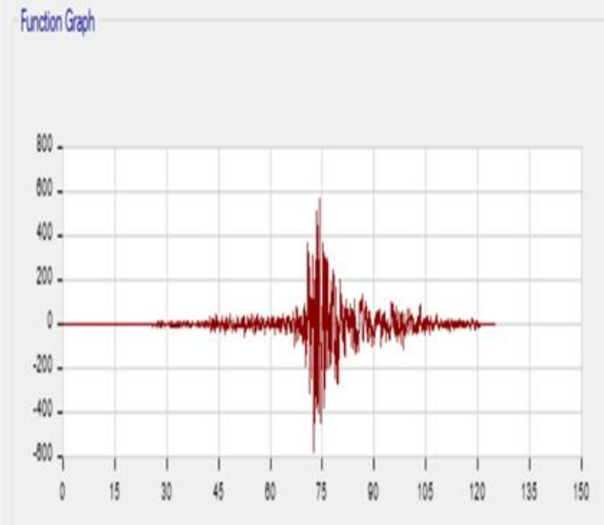


Figure 7: Time history graph of Imperial Earthquake, along X-direction and along Y-direction



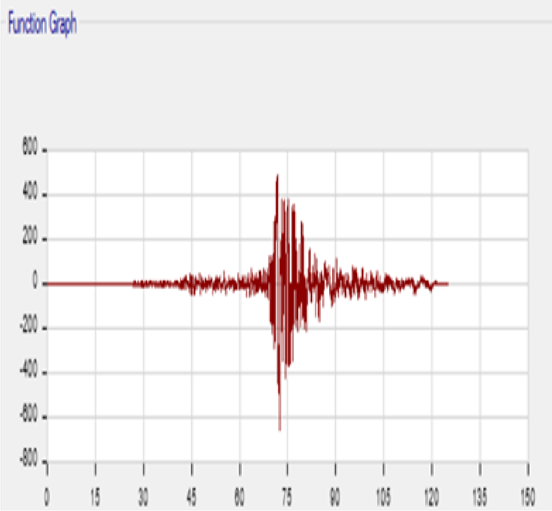


Figure 8: Time history graph of Turkey Earthquake, along X-direction and along Y-direction

3. *Results and discussion*

3.1 Fundamental Time Period

Every structure has a natural vibration frequency. A structure begins to vibrate when seismic forces are applied to it. The lower the frequency of the structure's vibration, higher will be the time period of vibration. Table 6 shows Fundamental time period for selected building models for this study.

Table 6: Fundamental time period for selected building models

Base condition	Building Type	Building configuration	Fundamental time period (sec)
Fixed	Regular	SB	0.833
		SBSB	0.636
		SF	1.01
		SFSB	0.79
		PG	1.205
	Irregular	SB	0.841
		SBSB	0.705
		SF	1.033
		SFSB	0.893
		PG	1.26
Flexible	Regular	SB	0.96
		SBSB	0.73
		SF	1.12
		SFSB	0.87
		PG	1.32
	Irregular	SB	0.973
		SBSB	0.808
		SF	1.15
		SFSB	0.998
		PG	1.38

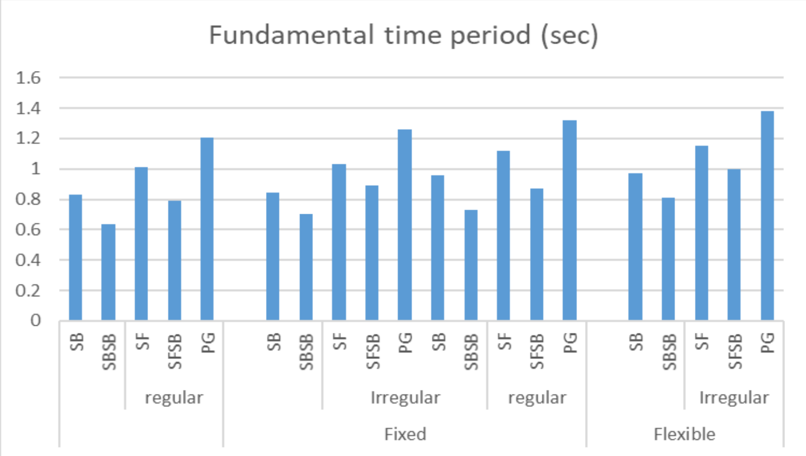


Figure 9: Comparison of fundamental time period for regular and irregular buildings

For regular buildings, the time period on a flexible base for step-back, step-back set-back, split foundation, split foundation set-back, and plain ground configurations increases by 15%, 15%, 11%, 10%, and 10%, respectively, compared to a fixed base. For irregular buildings, the time period on a flexible base for step-back, step-back set-back, split foundation, split foundation set-back, and plain ground configurations increases by 16%, 15%, 11%, 12%, and 10%, respectively, compared to a fixed base. Figure 9 shows that the fundamental time period for different building configurations with a flexible base is longer than for buildings with a fixed base. Additionally, the fundamental time period calculated using SSI models is longer than that calculated with a fixed base, indicating that changes in soil stiffness can have a significant effect on the fundamental period of vibration [17].

3.2 Base Shear

The maximum lateral force expected on the base of the structure due to seismic activity is referred to as base shear. When the ground shakes, it imparts lateral forces on a building. Base shear represents the cumulative effect of these forces. It is used as an indicator of the potential seismic load that the structure needs to withstand. The magnitude of base shear depends on various factors, including the building's mass, height, stiffness, and the ground motion characteristics of the earthquake. Figure 10 shows base shear comparison across slope for three earthquakes. Table 7 shows base shear of different building models for different selected earthquake.

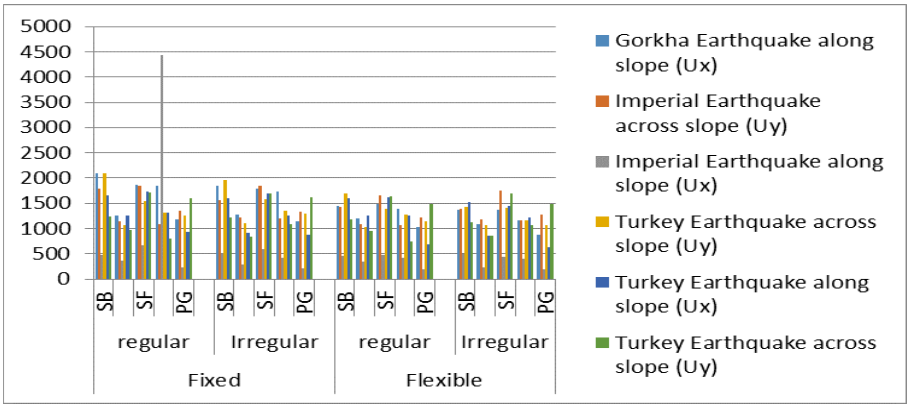


Figure 10: Base shear comparison for different building across slope for Gorkha Earthquake, Imperial Earthquake, and Turkey Earthquake

Table 7: Base Shear of different building models for different selected earthquake

Base condition	Building Type	Building configuration	Base Shear (KN) Gorkha Earthquake along slope (Ux)	Gorkha Earthquake across slope (Uy)	Imperial Earthquake along slope (Ux)	Imperial Earthquake across slope (Uy)	Turkey Earthquake along slope (Ux)	Turkey Earthquake across slope (Uy)
Fixed	Regular	SB	2090.87	1795.06	482.85	2096.2	1662.05	1239.23
		SBSB	1259.94	1141.08	353.97	1067.12	1265.6	964.7
		SF	1865.8	1836.98	674.21	1537.6	1736.45	1712.97
		SFSB	1844.07	1088.98	4441.23	1314.58	1322.08	798.44
		PG	1179.48	1344.21	238.53	1256.58	931.48	1606.9
	Irregular	SB	1843.69	1567.28	511.17	1963.49	1602.97	1217.73
		SBSB	1266.98	1221.33	289.21	1102.27	910.93	843.52
		SF	1795.58	1841.8	592.74	1574.38	1697.5	1695.53
		SFSB	1728.12	1205.25	424.09	1352	1263.37	1086.16
		PG	1144.96	1332.15	206.07	1297.79	879.13	1608.51
Flexible	Regular	SB	1449.44	1431.5	454	1695.67	1593.28	1175
		SBSB	1201.1	1081.23	353.53	1024.48	1259.02	945.82
		SF	1476.76	1655.5	474.42	1382.66	1621.13	1629.11
		SFSB	1396.91	1069.34	429.33	1271.03	1249.12	750.05
		PG	1019.57	1210.51	188.56	1137.3	686.35	1478.12
	Irregular	SB	1375.44	1391.58	502.97	1419.29	1524.47	1129.86
		SBSB	1077.6	1176.2	228.25	1071.4	862.05	857.01
		SF	1378.15	1744.48	440.36	1402.17	1451.86	1699.75
		SFSB	1168.05	1161.98	400.65	1160.3	1210.39	1058.18
		PG	869.19	1281.4	194.32	1071.89	620.32	1490.98

For regular buildings, the base shear in fixed base conditions for SB-R, SBSB-R, SF-R, SFSB-R, and PG-R is 31%, 5%, 21%, 24%, and 14% higher, respectively, than for flexible base conditions. For irregular buildings, the base shear in fixed base conditions for SB-IR, SBSB-IR, SF-IR, SFSB-IR, and PG-IR is 25%, 15%, 23%, 32%, and 24% higher, respectively, than for flexible base conditions. It is observed that for both regular and irregular cases, the base shear in flexible base conditions is lower than in fixed base conditions. This decrease occurs due to the increased lateral movement associated with a flexible base [27]. Among different building configurations, split foundation (SF) and step-back (SB) configurations exhibit higher base shear values, while step-back set-back (SBSB) and split foundation set-back (SFSB) configurations have lower base shear values. The SB configuration has higher base shear than SBSB due to an increase in the seismic weight of the structure [2].

3.3 Maximum Story Displacement

The maximum lateral displacement of the story with respect to ground is termed as maximum story displacement [28]. It is most commonly used parameters to observe the seismic performance of the structure. Table 8 shows the top story displacement of various building models under different earthquake scenarios.

Table 8: Top story displacement of different building models for different earthquakes

Base condition	Building Type	Building configuration	Top story displacement (mm)					
			Gorkha Earthquake		Imperial Earthquake		Turkey Earthquake	
			along slope (Ux)	across slope (Uy)	along slope (Ux)	across slope (Uy)	along slope (Ux)	across slope (Uy)
Fixed	Regular	SB	48.6	55.51	13.17	43.3	46.17	32.98
		SBSB	32.53	27.43	10.42	40.28	38.54	21.33
		SF	58.28	65.75	19.46	54.26	61.38	48.38
		SFSB	51.2	53.57	14.98	47.9	41.13	27.53
		PG	57.4	62.05	11.27	68.02	47.48	58.65
	Irregular	SB	47.63	48.1	13.73	42.53	47.29	25.96
		SBSB	41.39	22.4	10.48	40.23	34.94	18.41
		SF	57.31	61.91	16.908	52.89	59.38	46.42
		SFSB	54.95	34.88	19.11	50.33	54.102	26.8
		PG	44.78	64.88	13.6	66.219	40.37	63.95
Flexible	Regular	SB	55.47	71.13	19.08	50.11	59.58	54.15
		SBSB	46.41	34.86	13.08	44.7	42.99	25.99
		SF	64.8	68.74	20.49	59	67.3	69.39
		SFSB	56.51	57.09	17.54	56.12	61.75	41.69
		PG	63.78	64.9	13.43	69.05	50.04	63.03
	Irregular	SB	54.97	56.32	19.08	49.74	58.19	45.87
		SBSB	54.55	26.43	13.709	50.28	50.54	20.92
		SF	62.39	62.62	18.11	57.46	62.46	64.3
		SFSB	63.86	50.41	20.77	55.93	65.06	37.88
		PG	44.89	68.51	14.16	66.62	46.36	65.14

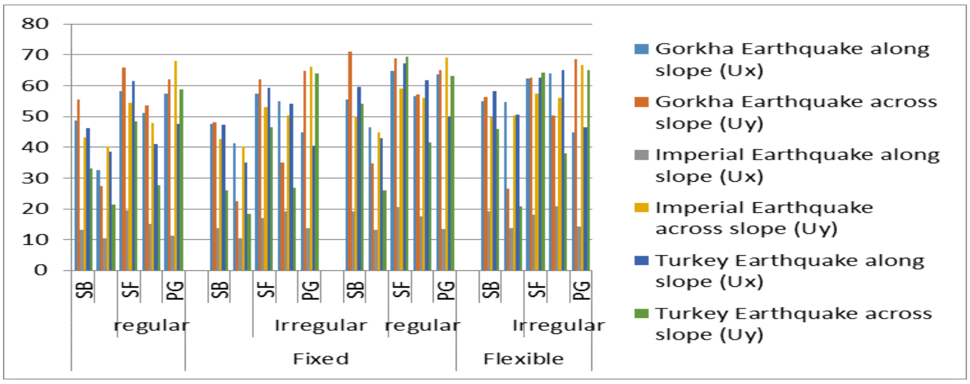
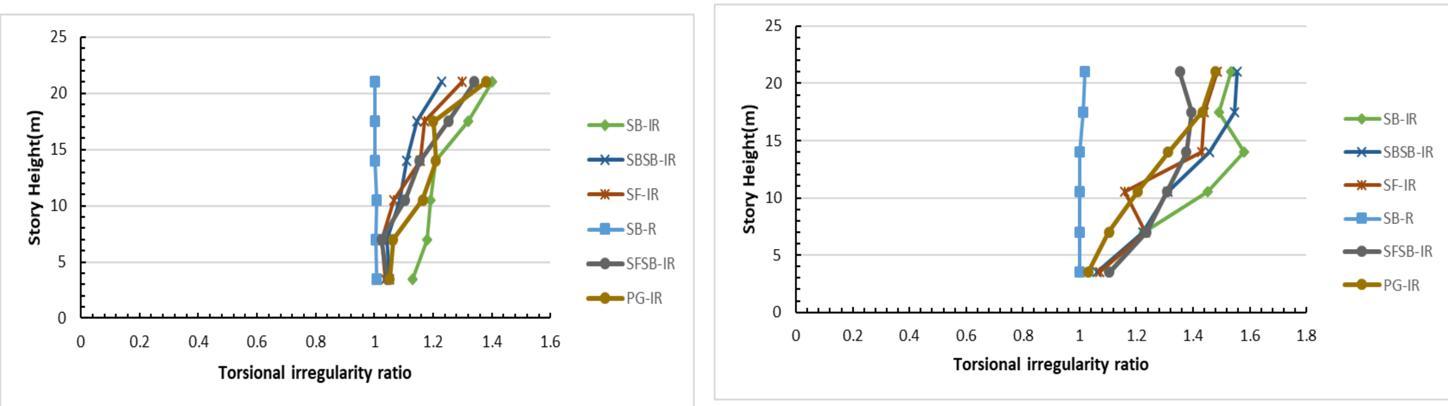


Figure 11: Comparison of top story displacement of different building with fixed and flexible base for Gorkha Earthquake, Imperial Earthquake and Turkey Earthquake

Figure 11 compares the top story displacement of different buildings with fixed and flexible bases during the Gorkha, Imperial, and Turkey earthquakes. The top story displacement of SB-R, SF-R, SFSB-R, and PG-R is found to have increased by 33%, 44%, 36%, and 43%, respectively, in comparison to SBSB-R, indicating that the split foundation has the maximum top displacement in the case of a fixed base along the slope direction. Similarly, the top story displacement of SB-IR, SF-IR, SFSB-IR, and PG-IR increases by 13%, 28%, 25%, and 8%, respectively, in comparison to SBSB-IR, showing that the split foundation has the maximum top displacement for irregular buildings with a fixed base along the slope direction. It is noticed that the top story displacement along the slope for regular buildings with a fixed base in SB, SBSB, SF, SFSB, and PG increases by 12%, 30%, 10%, 9%, and 10%, respectively, when a flexible base is provided. Additionally, the top story displacement across the slope for regular buildings with a fixed base in SB, SBSB, SF, SFSB, and PG increases by 22%, 21%, 4%, 6%, and 4%, respectively, when a flexible base is used. Among 20 different building models, the top story displacement along the slope and across the slope (in both directions) is higher for buildings with flexible bases than fixed bases for all selected earthquakes. The displacement for the SSI system is greater compared to the fixed base system [29]. Finally, the top story displacement for SBSB-R and SBSB-IR is found to be the lowest among the selected buildings, which occurs because the short-length columns in the sloped area stiffen the building, and due to this increased stiffness, the displacement is lower[2].

3.4 Torsional Irregularity Ratio

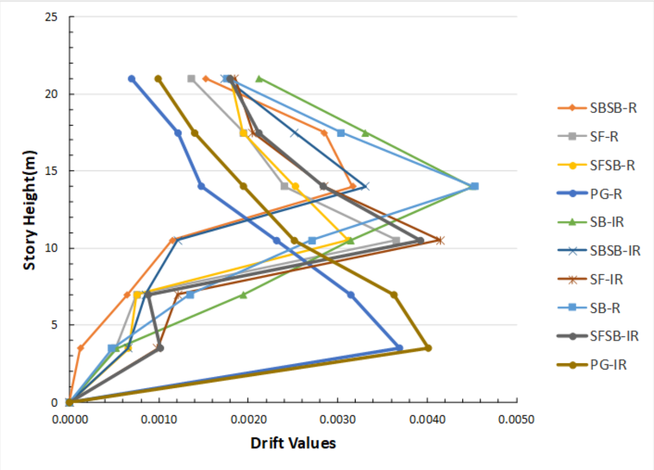
As per NBC 105:2020, when a floor's maximum horizontal displacement in the directionof the lateral force (applied at the center of mass) at one end of the story is greater than 1.5 times its minimum horizontal displacement at the far end of the same story in that direction, it is considered to have torsional irregularity. On plotting torsional irregularity ratio for different regular and irregular building in fixed and flexible base condition, it is found that the ratio is more in flexible base than that of fixed base, and the ratio is near to 1 for regular structure and much more than one for irregular structure. This is observed because in flexible base due to introducing the soil effect torsional irregularity ratio rises. For regular building torsional irregularity is small while for irregular building high torsional irregularity ratio is observed [6]. Figure 12 illustrates the torsional irregularity ratio along the slope based on the response spectrum for both fixed and flexible base conditions.



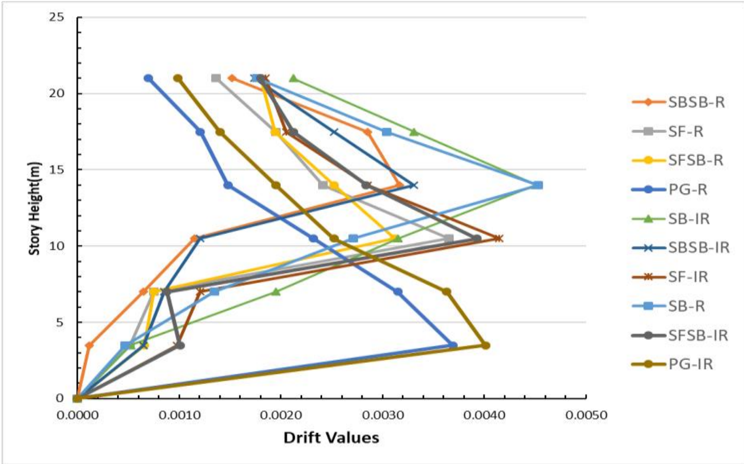
a) b)

Figure 12: Torsional irregularity ratio along slope by response spectrum a) fixed and b) flexible base conditions

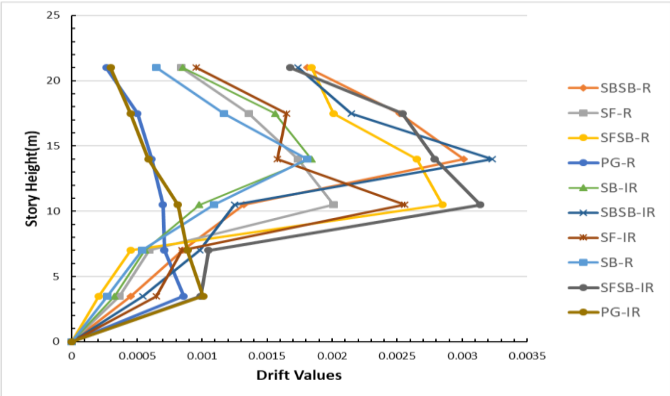
3.5 Inter-story Drift



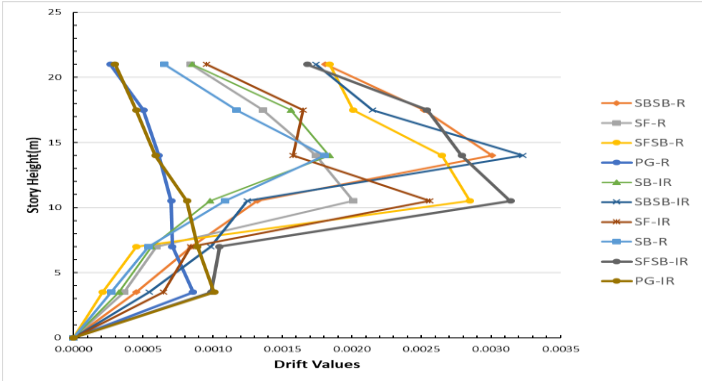
a)



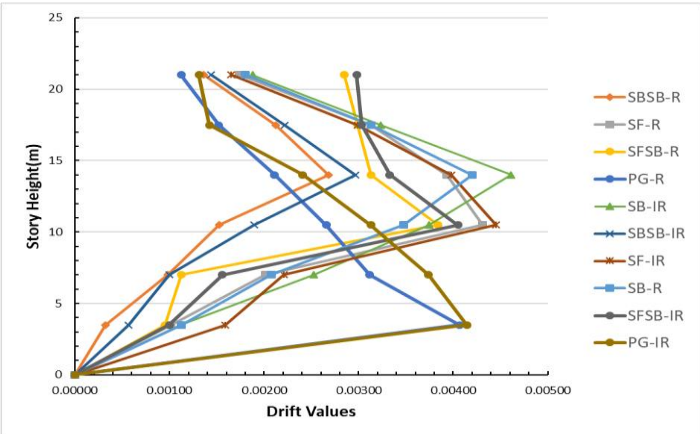
b)



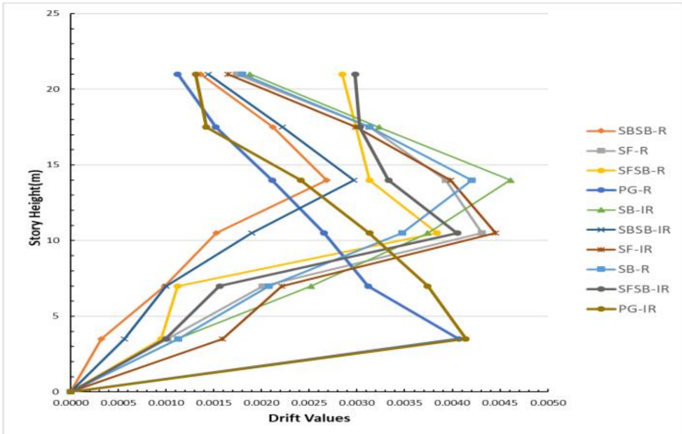
c)



d)



e)



f)

Figure 13: Distribution of Inter-Story Drift on Each Story for Fixed and Flexible Base Buildings Across Gorkha, Imperial, and Turkey Earthquakes (a-f)

Figure 13 illustrates the distribution of inter-story drift on each story for fixed and flexible base buildings during the Gorkha, Imperial, and Turkey earthquakes. Subfigures (a) and (b) show the drift distribution for fixed and flexible base buildings under the Gorkha Earthquake, respectively. Subfigures (c) and (d) present the same for the Imperial Earthquake, while subfigures (e) and (f) depict the inter-story drift for fixed and flexible base buildings during the Turkey Earthquake. These figures collectively illustrate the varying inter-story drift patterns in buildings with different base conditions across the Gorkha, Imperial, and Turkey earthquake events. They demonstrate the distribution of inter-story drift across each story, revealing higher drift in SF and SB buildings, with slightly greater drift observed in flexible base buildings compared to fixed base buildings.

4. Conclusions

In this study, 20 different buildings are modelled and analysed using the time history analysis method. The seismic behavior of buildings was studied while considering soil effects, and the results are compared with buildings having fixed base conditions. The buildings in slope areas and plain areas are modelled in FEM software ETABS, and the slope of the ground was checked for its stability. The conclusions of this study are as follows: the base shear decreases when the effect of soil is considered due to an increase in the structure's effective damping ratio and natural time period. The flexible base provides more lateral movement at the base than a fixed base, meaning buildings with fixed bases have higher base shear than buildings with flexible bases. The fundamental time period of a building increases when SSI is considered. In buildings considering the soil effect, the flexibility of the base increases, reducing stiffness, and since the time period is inversely proportional to stiffness, the time period increases. Hence, fixed base buildings have lower time periods compared to flexible base buildings.

The time period for plain ground buildings was found to be higher than for all other building configurations due to higher seismic weight, a larger geometrical plan, and a flexible foundation. In contrast, the time period for step-back set-back (SBSB) buildings was found to be the lowest for both regular and irregular cases due to the lower seismic weight in setback configuration buildings. Comparing different building configurations, split foundation (SF) and step-back (SB) configurations have higher values of base shear, while step-back set-back (SBSB) and split foundation set-back (SFSB) configurations have lower values of base shear. This is due to the reduced seismic weight in the lower floors of the set-back configuration. The top story displacement along the slope and across the slope (both directions) is higher for buildings with flexible bases than for fixed bases in all selected earthquakes because the flexible base permits the structure to sway more freely, resulting in larger story displacement. The torsional irregularity is influenced by the base condition, with buildings on fixed bases being stiffer and having less torsional irregularity. When considering the soil effect, the building's stiffness reduces, and torsional irregularity is higher in buildings with flexible bases. Irregularly shaped buildings on slopes have higher torsional irregularity ratios than regular buildings on slopes, while regular plain ground buildings exhibit much less torsional irregularity compared to the other configurations.

Conflicts of interest statement

The authors declare no conflicts of interest for this study.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Y. Aggarwal and S. K. Saha, "Seismic performance assessment of reinforced concrete hilly buildings with open story," in *Elsevier*, 2021, pp. 224–238.
2. A. Dangol and G. B. Motra, "Seismic response of buildings resting on hill slope," in *2021*, pp. 115–122.
3. S. Kumar and D. Paul, "A simplified method for elastic seismic analysis of hill buildings," *J. Earthq. Eng.*, vol. 2, no. 02, pp. 241–266, 1998.
4. Z. Mohammad, A. Baqi, and M. Arif, "Seismic response of RC framed buildings resting on hill slopes," *Procedia Eng.*, vol. 173, pp. 1792–1799, 2017.
5. N. Kapoor, V. Bansal, and M. Jain, "Development of creative problem solving-based framework for site planning in hill areas," *Front. Archit. Res.*, vol. 9, no. 2, pp. 450–466, 2020.
6. B. Khanal and H. Chaulagain, "Seismic elastic performance of L-shaped building frames through plan irregularities," in *Elsevier*, 2020, pp. 22–36.
7. R. Jarapala and K. C. Biswal, "Dynamic behavior of vertically irregular sloping ground buildings," *Asian J. Civ. Eng.*, vol. 22, no. 1, pp. 125–136, 2021.
8. P. Song, S. Guo, W. Zhao, and Q. Xin, "Seismic response analysis of reinforced concrete frame structures considering slope effects," *Appl. Sci.*, vol. 13, no. 8, p. 5149, 2023.
9. W. Wang and X. Wang, "Seismic behaviour of structures under long-duration ground motions: A review," in *Elsevier*, 2023, pp. 1224–1236.
10. S. C. Dutta, P. S. Mukhopadhyay, R. Saha, and S. Nayak, "2011 Sikkim Earthquake at Eastern Himalayas: Lessons learnt from performance of structures," *Soil Dyn. Earthq. Eng.*, vol. 75, pp. 121–129, 2015.
11. P. Sarkar, A. M. Prasad, and D. Menon, "Vertical geometric irregularity in stepped building frames," *Eng. Struct.*, vol. 32, no. 8, pp. 2175–2182, 2010.
12. L. Liu, R. Zhong, Y. Yu, and R. Li, "Study on seismic performance of reinforced concrete stilted building with steel braces in mountainous areas," in *Structures*, Elsevier, 2023, pp. 2199–2216.
13. M. J. Shabani, M. Shamsi, and M. Zakerinejad, "Slope topographic impacts on the nonlinear seismic analysis of soil-foundation-structure interaction for similar MRF buildings," *Soil Dyn. Earthq. Eng.*, vol. 160, p. 107365, 2022.
14. K. V. Babu, S. S. R. Krishna, and V. Malagavelli, "Seismic analysis of multi-storey building on sloping ground and flat ground by using ETABS," in *IOP Publishing*, 2023, p. 012004.
15. D. Chhangchha, "Televising 'Kathmandu' (Dissecting the Indian Media's 'Guerilla Broadcasting' of Nepal During the Crisis)," Department of Sociology, 2019.
16. F. Behnamfar and M. Banizadeh, "Effects of soil-structure interaction on distribution of seismic vulnerability in RC structures," *Soil Dyn. Earthq. Eng.*, vol. 80, pp. 73–86, 2016.
17. S. Dhakal and H. Chaulagain, "Seismic behaviour of plan irregular reinforced concrete buildings considering soil effects," *J. Build. Pathol. Rehabil.*, vol. 8, no. 1, p. 46, 2023.

18. M. Mekki, S. Elachachi, D. Breysse, and M. Zoutat, "Seismic behavior of RC structures including soil-structure interaction and soil variability effects," *Eng. Struct.*, vol. 126, pp. 15–26, 2016.
19. M. Kamal, M. Inel, and B. T. Cayci, "Seismic behavior of mid-rise reinforced concrete adjacent buildings considering soil-structure interaction," *J. Build. Eng.*, vol. 51, p. 104296, 2022.
20. I. Negrin, M. Kripka, and V. Yepes, "Metamodel-assisted meta-heuristic design optimization of reinforced concrete frame structures considering soil-structure interaction," *Eng. Struct.*, vol. 293, p. 116657, 2023.
21. E. Ahmadi, M. Kiani, F. Paytam, and F. Khoshnoudian, "Equivalent linearization parameters of soil-MDOF structure systems subjected to pulse-like earthquakes," *Soils Found.*, vol. 58, no. 6, pp. 1371–1382, 2018.
22. P. Yadav, A. Padade, P. Dahale, and V. Meshram, "Analytical and experimental analysis of retaining wall in static and seismic conditions: A review," *Int. J. Civ. Eng. Technol. IJCIET*, vol. 9, no. 2, pp. 522–530, 2018.
23. Z. Qian, A. J. Li, W. Chen, A. Lyamin, and J. Jiang, "An artificial neural network approach to inhomogeneous soil slope stability predictions based on limit analysis methods," *Soils Found.*, vol. 59, no. 2, pp. 556–569, 2019.
24. L. Chen, W. Zhang, F. Chen, D. Gu, L. Wang, and Z. Wang, "Probabilistic assessment of slope failure considering anisotropic spatial variability of soil properties," *Geosci. Front.*, vol. 13, no. 3, p. 101371, 2022.
25. T. Yang, J. F. Zou, and Q. J. Pan, "Three-dimensional seismic stability of slopes reinforced by soil nails," *Comput. Geotech.*, vol. 127, p. 103768, 2020.
26. H. Xu, X. He, B. Pradhan, and D. Sheng, "A pre-trained deep-learning surrogate model for slope stability analysis with spatial variability," *Soils Found.*, vol. 63, no. 3, p. 101321, 2023.
27. Zaidi, S.A., Naqvi, T. and Ibrahim, S.M., 2021. Study on the effects of seismic soil-structure interaction of concrete buildings resting on hill slopes. *Materials Today: Proceedings*, *43*, pp.2250-2254.
28. A. Souhaibou and L. Zhi Li, "A comparative study on the lateral displacement of a multi-story RC building under wind and earthquake load actions using base shear method and ETABS software," *Mater. Today Proc.*, 2023.
29. E. Demirol and A. S. Ayoub, "Inelastic displacement ratios of SSI systems," *Soil Dyn. Earthq. Eng.*, vol. 96, pp. 104–114, 2017.