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Numerical & Dynamic Analysis of Sloped Buildings

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ABSTRACT

Seismic history of India shows that the zones of upper seismic activity and better magnitudes are mostly presents in hilly terrains of northern and north eastern regions. Also these places are more likely attracts peoples from plains for various purposes varying from adventure, tourism, religious and also for resolving problem of habitat to decrease in habitable land within the urban areas. These all purposes may cause resolve the matter of migration of peoples from hilly regions to lack of resources, which may provide aids to comply their basic needs. Buildings constructed on slopes are different from those in plains. They will be irregular and unsymmetrical in horizontal and vertical planes, and torsion ally coupled. Hence, they are susceptible to severe damage when affected by earthquake ground motion. We cannot avoid the long run earthquakes but the preparedness and safe building construction practices for earthquakes can certainly reduce the extent of injury and loss of both property and life. this is often often because of the actual fact that the columns within the bottom storey are of varied heights in such how that column in one end could also be a brief column and column in other end could also be an extended column. Dynamic characteristics of hill buildings are somewhat different from the buildings on flat ground. Torsional effect of such buildings is broken for having the difference stiffness and mass along horizontal and vertical plane during ground, motion .In this review paper, behaviour of two storied sloped frame having step back configuration is analyzed for sinusoidal ground motion with different slope angles i.e., 15°, 20° and 25° with an experimental set up and are validated by developing a Finite Element code executed in structural analysis tool STAAD Pro. by performing a linear time history analysis. From the above analysis, it has been observed that as the slope angle increases, stiffness of the model increases due to decrease in height of short column and that results in increase of earthquake forces on short column which is about 75% of total base shear and chances of damage is increased considerably due to the formation of plastic hinges therefore proper analysis is required to quantify the effects of various ground slopes.

Keywords-Sloped Buildings, STAAD PRO, Time history Analysis, Finite Element Code

1. INTRODUCTION

Seismic history of India shows that the zones of upper seismic activity and better magnitudes are mostly presents in hilly terrains of northern and north-eastern regions. As well these places are more likely attracts peoples from plains for various purposes varying from adventure, tourism, religious and also for resolving problem of habitat to decrease in habitable land in the urban areas. These all purposes may cause resolve the matter of migration of peoples from hilly regions to lack of resources which can provide aids to comply their basic needs.Building structures subjected to seismic forces are always more susceptible to collapse and if this phenomenon occurs on a sloping ground building structures as on hills which lies at some inclination angle to the bottom, chances of injury suddenly increase far more thanks to increase in lateral forces like seismic and wind on short column on upward hill side and on the short column side more number of plastic hinges forms. Building structures built on slopey terrain differs from those, which are on plains because sloping structures have irregularity in horizontally also as vertically. Dynamic characteristics of hill buildings are significantly different from the buildings resting on flat topography, as these are irregular and unsymmetrical. Earthquake is the most disastrous and unpredictable phenomenon of nature. When a structure is subjected to seismic forces it does not cause loss to human lives directly but due to the damage cause to the structures that leads to the collapse of the building and hence to the occupants and the property. Mass destruction of the low and high rise buildings in the recent earthquakes leads to the need of investigation especially in a developing country like India. Structure subjected to seismic/earthquake forces are always vulnerable to damage and if it occurs on a sloped building as on hills which is at some inclination to the ground the chances of damage increases much more due to increased lateral forces on short columns on uphill side and thus leads to the formation of plastic hinges. Structures on slopes differ from those on plains because they are irregular horizontally as well as vertically. In north and northeastern parts of India have large scale of hilly terrain which fall in the category of seismic zone IV and V. Recently Sikkim (2011), Doda (2013) and Nepal earthquake (2015) caused huge destruction. In this region there is a demand of construction of multistory RC framed buildings due to the rapid urbanization and increase in economic growth and therefore increase in population density. Due to the scarcity of the plain terrain in this region there is an obligation of the construction of the buildings on the sloping ground. In present work, a two storeyed framed building with an inclination of 15°, 20° and 25° to the ground subjected to sinusoidal ground motion is modelled with an experimental setup and validated with a finite element coding executed in the MATLAB platform and results obtained are validated by performing linear time history analysis in structural analysis and design software (STAAD Pro.).

2. LITERATURE REVIEW

Dynamic analysis performed on RC space frame building structures with three different configurations like step back, step back –set back and set back buildings and analytical results are presented. Response spectrum method is used for three dimensional analyses in which torsioneffect is also considered generated from accidental eccentricity. The seismic response characteristics i.e. natural time period, top storey sway and base shear. According to building structures configuration best suitability of column on sloping ground is analyze. From analytical results it is observed that step back set back buildings are found to be more suitable on the hilly terrain.

Ravikumar et al. (2012) studied two kinds of irregularities in building model namely the plan irregularity with geometric and diaphragm discontinuity and vertical irregularity with setback and sloping ground. Pushover analysis was performed taking different lateral load cases in all three directions to identify the seismic demands. All the buildings considered are three storied with different plan and elevation irregularities pattern. Plan irregular models give more deformation for fewer amounts of forces where the vulnerability of the sloping model was found remarkable. The performances of all the models except sloping models lie between life safety and collapse prevention. Hence it can be concluded that buildings resting on sloping ground are more prone to damage than on buildings resting on flat ground even with plan irregularities.

Sreerama and Ramancharla (2013) observed that recent earthquakes like Bihar-Nepal (1980), Shillong Plateau and the Kangra earthquake killed more than 375,000 people and over 100,000 of the buildings got collapsed. Dynamic characteristics of the buildings on flat ground differ to that of buildings on slope ground as the geometrical configurations of the ` 7 building differ horizontally as well as vertically. Due to this irregularity the centre of mass and the centre of stiffness does not coincide to each other and it results in torsional response. The stiffness and mass of the column vary within the storeys that result in increase of lateral forces on column on uphill side and vulnerable to damage. In their analysis they took five G+3 buildings of varying slope angles of 0, 15, 30, 45, 60° which were designed and analysed using IS-456 and SAP2000 and further the building is subjected and analysed for earthquake load i.e., N90E with PGA of 0.565g and magnitude of M6.7. They found that short column attract more forces due to the increased stiffness. The base reaction for the shorter column increases as the slope angle increases while for other columns it decreases and then increases. The natural time period of the building decreases as the slope angle increases and short column resist almost all the storey shear as the long columns are flexible and cannot resist the loads.

Patel et al. (2014) studied 3D analytical model of eight storied building was analysed using analysis tool ETabs with symmetric and asymmetric model to study the effect of variation of height of column due to sloping ground and the effect of concrete shear wall at different locations during earthquake. In the present study lateral load analysis as per seismic code was done to study the effect of seismic load and assess the seismic vulnerability by performing pushover analysis. It was observed that vulnerability of buildings on sloping ground increases due to formation of plastic hinges on columns in each base level and on beams at each storey level at performance point. The number of plastic hinges are more in the direction in which building is more asymmetric. Buidings on sloping ground have more storey displacement as compared to that of buildings on flat ground and without having shear wall. Presence of shear wall considerably reduces the base shear and lateral displacement.

Birajdar and Nalawade (2004) performed 3D analysis of 24 RC buildings with three different configurations like set back, step back and step set back building. Response spectrum analysis including the torsional effect has been carried out. The dynamic properties which are top storey displacement, base shear and fundamental time period have been studied considering the suitability of buildings on sloping ground. In this study three types of configuration mentioned above are used in two (step back and step set back building) are on sloping ground while the third one (set back) is on plain ground. The sloping angle is taken as 27 degrees. The number of stories taken is from 4 to 11 and hence total of 24 RC buildings where studied. Set back building- As the number of stories increases there is a linear increase in top storey displacement and time period for the earthquake in longitudinal direction. The value of top storey displacement and fundamental time period in transverse direction are higher compared to longitudinal direction due to increase in torsional moments due to effect of static and accidental eccentricity. From design point of view proper attention should be given to the strength, orientation and ductility demand of shortest column at ground level to ensure its safety under worst combination of load case in X and Y direction. Step set back building-The results obtained in the static and dynamic analysis do not differ substantially as in the case of step back building. The top storey displacement is about 3.8 to 4 times higher in transverse direction than the corresponding values in longitudinal direction. Set back building- Shear forces induced in set back building is found to be least in comparison with the other two buildings. The distribution of shear forces in set back building is even and there is little problem of development of torsional moment. Step back buildings are found to be most vulnerable compared to other configurations and the development of torsional moment is highest in step back building. The column at ground level is prone to damage as it is worst affected.

Singh et al. (2012) carried out an analytical study using linear and nonlinear time history analysis. They considered 9 story RC frame building (Step back) with 45 degrees to the horizontal located on steep slope. The number of storeys was 3 and 9 and 7 bays along the slope and 3 across the slope. They took 5 set of ground motions i.e., 1999 Chi-Chi, 1979 Imperial Valley, 1994 Northridge , 1971 San Fernando , 1995 Kobe from strong motion database of pacific Earthquake Engineering Research Centre (PEER). They observed that almost all the storey shear is resisted by the short column. The effect of torsional irregularity is represented by the ratio of maximum to average inter storey drifts ($\Delta max/\Delta avg$) in a storey. They observed the step back buildings are subjected to considerable amount of torsional effects under cross slope excitations.

Babu et al. (2012) performed pushover analysis of various symmetric and asymmetric structures constructed on plain as well as on sloping ground. They conducted analysis using structures with different configurations which are plan symmetry and asymmetry having different bay sizes. They considered a 4 storey building in which one storey is above ground level and it is constructed at a slope of 30 degree. They observed that the short column subjected to worst level of severity and lie beyond collapse prevention (CP) from pushover analysis. They obtained displacement as 104 mm and base shear as 2.77*103 kN. Based on these results they developed pushover curves with X-axis as displacement and Y-axis as base shear and gave various comparisons for the cases they considered. They found that up to failure limit for maximum displacement by symmetric structure is 70% and by asymmetric building is 24% more than the structure on plain ground. They concluded that structure is more critical in elevation irregularity than in plan irregularity.

Prashant and Jagadish (2013) studied the seismic response of one way slope RC building with a soft storey. They have focussed their work to the buildings with infill wall and without infill wall i.e., bare frame. They carried out pushover analysis in a 10 storey building which ` 10 include bare frame with and without infill wall. The buildings were situated at an inclination of 27 degrees to the horizontal and having 5 bays along the slope. Frame system considered was specially moment resisting frame (SMRF). In this study, they found that time period of building consisting of bare frame is 1.975 sec. which is about 96-135% higher as compared to the building having infill walls which is due to the reason of increased stiffness of the building and hence the increase in frequency. Further they observed that the displacement of the building is more in case of bare frame due to reduced stiffness and absence of infill wall. They also found that the base shear in infilled frames is about 250% more as compared to bare frame. Therefore formation of plastic hinges is more in bare frame model consisting of soft storey.

Halkude et al. (2013) conducted seismic analysis of buildings resting on sloping ground by varying number of bays and slope inclination. They studied the dynamic characteristics of the building i.e., base shear, top storey displacement and natural time period with respect to variation in number of stories and number of bays along the slope and hill slope. They considered a step back building of 4 to 11 storey and 3 to 6 bays in longitudinal directions. They have not considered the variation of bays in transverse direction so they have kept the single bay in Y-direction. The slope angles taken are 16.32°, 21.58°, 26.56° and 31.50° with the horizontal and seismic zone III. In all configurations it was observed that base shear increases with increase in number of storey, increases with increase in number of bays but decreases with increase in slope angle. Comparing within different configurations, step back building have higher base shear with respect to the step set back buildings. They also found time period increases with the increase in number of storey in both the configurations, with the increase in number of bays in step back building time period increases while in case of step set back building time period decreases. As the slope angle increases the stiffness of the building increases therefore the time period in all the configurations decreases. Top storey ` 11 displacement decreases with the increase in hill slope, increases with the increase in the number of storey and decreases when the number of bays is increased. They concluded that more number of bays are better as this increases the time period and therefore it reduces top storey displacement.

3. OBJECTIVES OF THE PROJECT

- The experimental study is undertaken with a two storied sloped frame model mounted rigidly to a shake table, capable of producing sinusoidal acceleration to study the dynamic response of sloped frame due to change of slope inclination by keeping the total height of frame constant.
- Finite element method is used as a numerical tool to solve the governing differential equation for undamped free vibration to find the natural frequency of model.
- Newmark method is used for numerical evaluation of dynamic response of the frame model.
- Linear time history analysis is performed using structural analysis tool i.e., STAAD Pro. by introducing compatible time history as per spectra of IS 1893 (Part 1):2002 For 5 % damping at rocky soil.

4. PROPOSED METHODOLOGY

4.1 EXPERIMENTAL WORKS

This chapter deals with experimental works performed on free vibration and forced vibration on sloped frame model. The results obtained from the experimental analysis are compared with the finite element coding. *The work performed is categorized into three sections which are as follows:-*

- Details of Laboratory Equipments
- Fabrication and Arrangement
- Free and Forced Vibration Analysis

4.2 EXPERIMENTAL MODELING

1. Three Mild Steel plates- In this model, there are three mild steel plates, two of same sizes and the other of different size. Plate no. 1 and 2 are used in each storey level and plate no. 3 used as base plate. The dimension of plates is shown in table 4.1.

Table 4.1: Dimensions and Mass of mild steel plate

Plate No.	Dimension (cm)	Mass (kg)
Plate 1 & 2	50x40x1	15.44
Plate 3	70x40x1	21.76

2. Four Threaded rods- The threaded rods are used as columns which are connected with mild steel plates in each storey level. The diameter of threaded rod used is 7.7 mm.

3. Nuts and washers- The number of set of Nuts and washers used is 32. Each 8 sets for two storey levels to connect threaded rods with steel plates and 8 nos. for base plate and 8 nos. for connecting threaded rod to the plate of shake table.

4. Wooden logs and planks- The wooden logs and planks are used to obtain firm ground. The logs of wood are inserted in between base plate and shake table to fill the space between inclined base plate and platform of shake table. Wedge shaped small logs of wood are also used which facilitates in erect fitting of column with plates.

5. Shake Table- Shake table is used to simulate the seismic event happening on the site. The shake table consists of horizontal, unidirectional sliding platform of size 1000 mm x 1000 mm. It consists 81 tie down points at a grid of 100 mmx 100mm. The maximum payload is 100 kg. The maximum displacement of the table is 100 mm (±50 mm). The rectangular platform is used to test the response of structures to verify their seismic performance. In this table the test specimen is fixed to the platform and shaken. The frequency of the table is controlled by a control panel which is run by input voltage of 440 volts.

6. Vibration Analyser- Vibration analyser (VA) is an important component to condition monitoring program. It is also referred as predictive maintenance. It is used to measure the acceleration, velocity and displacement displayed in time waveform (TWF). But the commonly used spectrum is that derived from a Fast Fourier Transform (FFT). Vibration Analyser provides key information about the frequency information of the model.

7. Control Panel- This device is used to allow the user to view and manipulate the forcing frequency of the model. The range of frequency available for the operation of shake table is from 0 to 20 Hz.

8. Personal Computer– The computer system used to perform the test consists of Intel(R) Core (TM) i5 processor with 4 GB RAM, 32-bit operating system and running Windows 7 professional. The software used for data acquisition is NV Gate. This software facilitates user to conduct the FFT analysis of the received signal and record various graphs i.e., time versus acceleration, time versus velocity and time versus displacement. All the records obtained during the vibration of the model is simultaneously displayed in the monitor.

9. Accelerometer-It is a device which is used to measure the proper acceleration. Proper acceleration does not meant to be the co-ordinate acceleration (rate of change of velocity with tim) but it is the acceleration which it experiences due to the free fall of an object. Accelerometer transfers its record to the vibration analyser which is received by computer and transforms it to a signal.

4.3 FABRICATION AND ARRANGEMENT

The holes of 8 mm diameter are driven in the plates 4 nos. through which threaded bar passes. The holes are made at a radial distance of 5√ cm from each corner of the plate. In plate 3 slot cut of 2 cm is done at a radial distance of 5√ cm from each corner of base plate which is connected to platform of shake table. A slot cut of 5 cm is made on base plate to accommodate slope angle of 15°, 20° and 25° at a distance of 41 cm from slot cut of connected leg. The threaded rods are passed through these slots and holes and are fixed to the platform using nuts and washers.

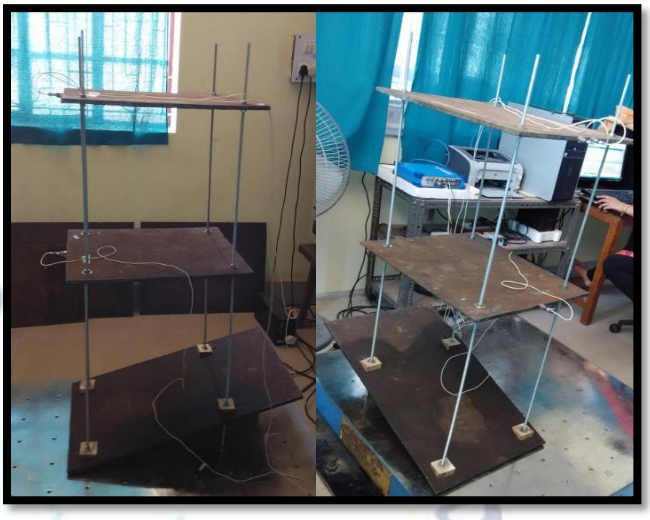
Now the base plate is fixed maintaining the slope angle of 15°, 20° and 25° (one at a time). Now the Plate 1 and 2 are fixed at a clear distance of 51 cm and 92.5 cm from connected end of base plate respectively. The screw is tightened well to ensure proper fixity. The wooden logs are inserted in between base plate and platform to achieve firm base similar to that of a sloping ground. Now three accelerometers are connected to the plates, two of them with plate 1 and one with plate 2. These accelerometers are connected with the vibration analyser and this analyser is connected to the computer. The readings obtained due to the vibration are recorded through the accelerometer. One LVDT (Linear Variable Displacement Transducer) is also used to record the displacement of the shake table at the time of forced vibration. The maximum amplitude of the ground motion is kept 5 mm. The entire tests were conducted in the "Structural Engineering" laboratory of VMIT, Nagpur.

4.4 FREE AND FORCED VIBRATION ANALYSIS

Free Vibration Analysis- A vibration is said to be free when a mechanical system is set off to an initial input and then set to vibrate freely. The vibrating system will damp to zero before that it will provide one or more natural frequency. In this experimental model, free vibration analysis is performed to obtain the natural frequencies of the model. By conducting FFT analysis we obtained two dominating frequencies which are natural frequencies. These two frequencies will be used as a basis for further analysis. A slight push is given to the Plate 1 (Top storey) and the readings are taken and by doing FFT analysis natural frequency of the system are obtained.

Forced Vibration Analysis- A forced vibration is one in which system is subjected to disturbance varying with time. The disturbance may be load, displacement or velocity and it may be periodic or non-periodic, transient or steady. The periodic input may be harmonic or non-harmonic in nature. Example vibration of building subjected to earthquake. If the frequency of vibration of the model is equal to its natural frequency then the system will be said to have condition of resonance. The response of the system is large during the resonance and it may be of such magnitude that it may lead to failure of structure.

4.5 EXPERIMENTAL MODELS



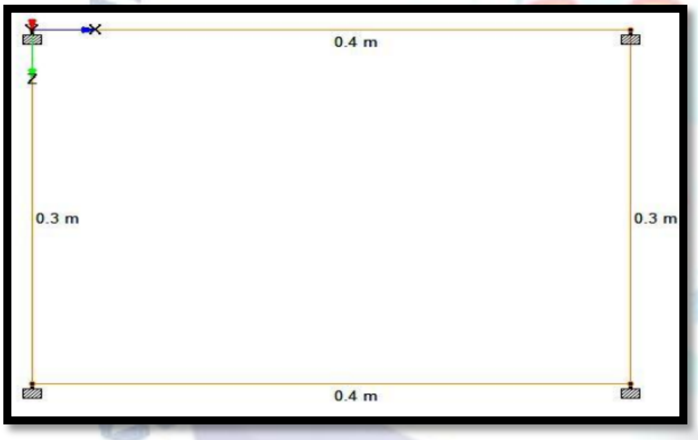
[Fig.4.1: Experimental Model for 15° slope]

[Fig.4.2: Experimental Model for 20° slope]

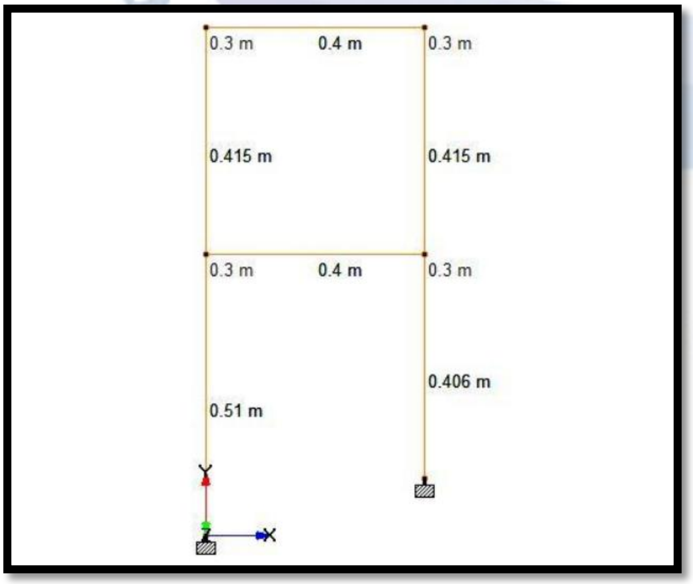
[Fig.4.3: Experimental Model for 25° slope]

4.6 STAAD PRO MODELING

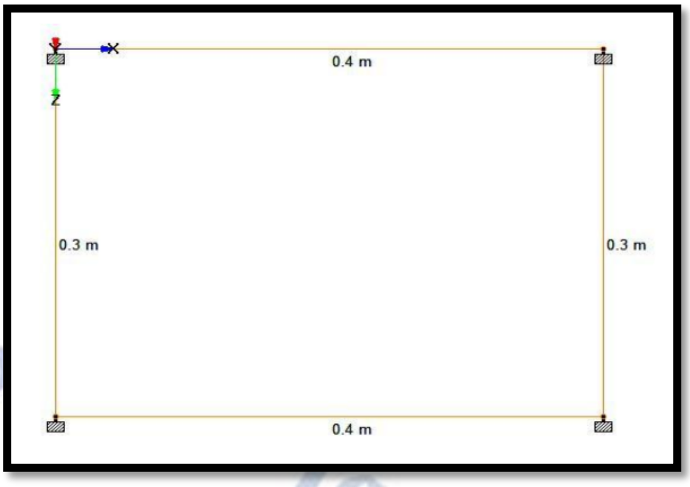
In this study, numerical modeling in STAAD Pro platform of the sloped frame is described. The plan and elevation of two storied sloped building subjected to ground motion record as per spectra of IS 1893 (Part 1)-2002 is shown. There are three different slope angle taken which are 15°, 20° and 25°. All the material properties of steel beam and column element are explained. Gravity loads considered are also explained. At the end the size of the elements are described. In this article, modelling is done in STAAD Pro. A two storied sloped frame model with plan and elevation is shown from figure 4.14 to figure 4.19 with different slope angle. But the total height of the building in all the three model is kept same i.e., 92.5cm of which height of first floor is 51 cm and 41.5 cm for the second floor. The length of bay is taken as 40 cm in longitudinal direction and 30 cm in transverse direction.



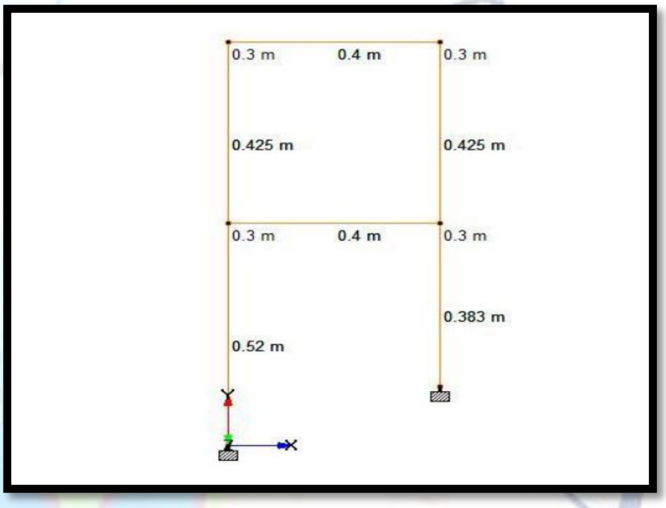
[Fig.4.4: Plan of sloped frame for 15° inclination]



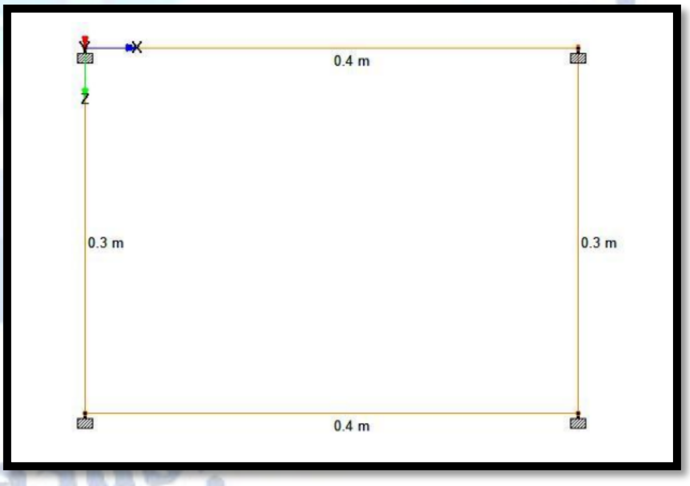
[Fig.4.5: Elevation of sloped frame for 15° inclination]



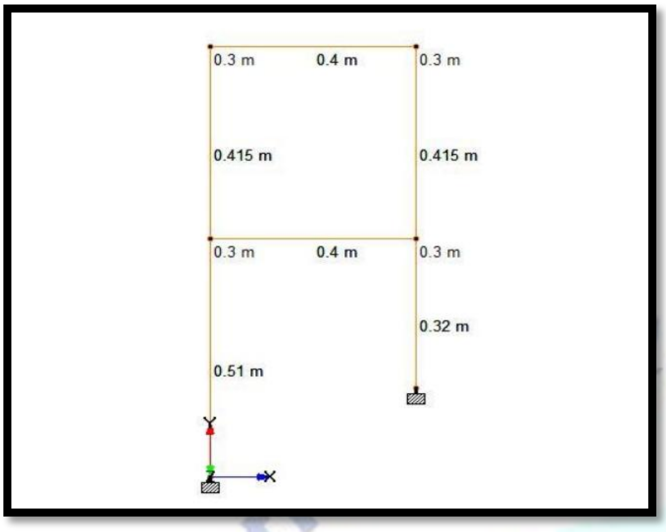
[Fig.4.6: Plan of sloped frame for 20° inclination]



[Fig.4.7: Elevation of sloped frame for 20° inclination]



[Fig.4.8: Plan of sloped frame for 25° inclination]



[Fig.4.9: Elevation of sloped frame for 25° inclination]

5. RESULTS AND DISCUSSIONS

Table 5.1: Natural frequencies of model with different slope inclinations

Type of Model	Natural Frequency (Hz)	
	Mode 1	Mode 2
15°	2.05	5.80
20°	2.2	5.945
25°	2.6	6.55

Table 5.2: Maximum Storey Displacements (Absolute) for frame model of 15° inclination

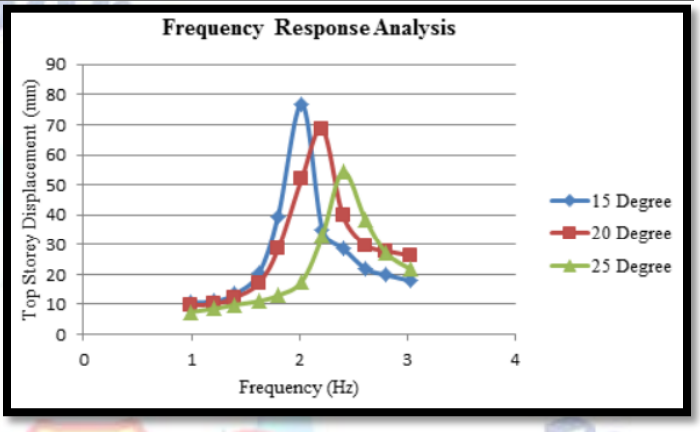
Storey No.	Maximum Storey Displacement (mm)
1	55.2
2	76.6

Table 5.3: Maximum Storey Displacements (Absolute) for frame model of 20° inclination

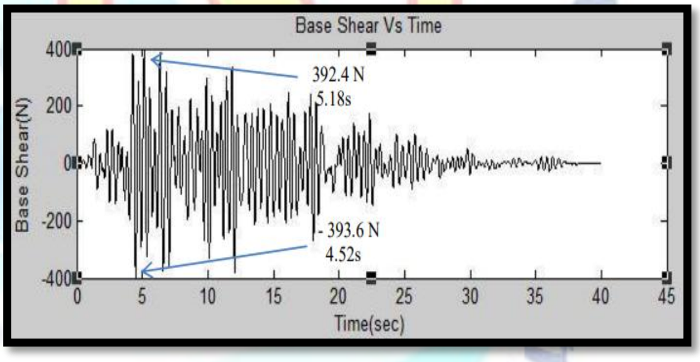
Storey No.	Maximum Storey Displacement (mm)
1	44
2	68.3

Table 5.4: Maximum Storey Displacements (Absolute) for frame model of 25° inclination

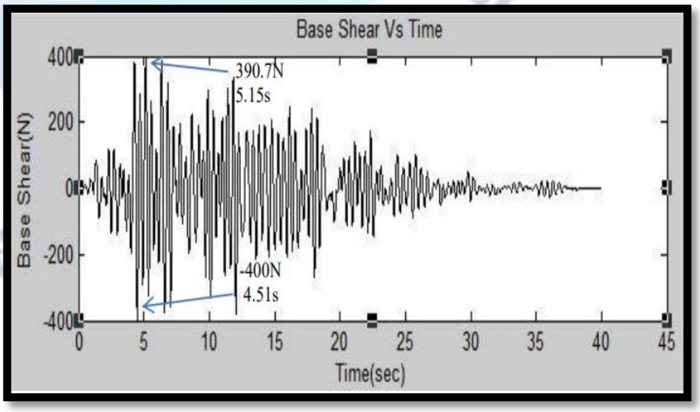
Storey No.	Maximum Storey Displacement (mm)
1	32.9
2	58.3



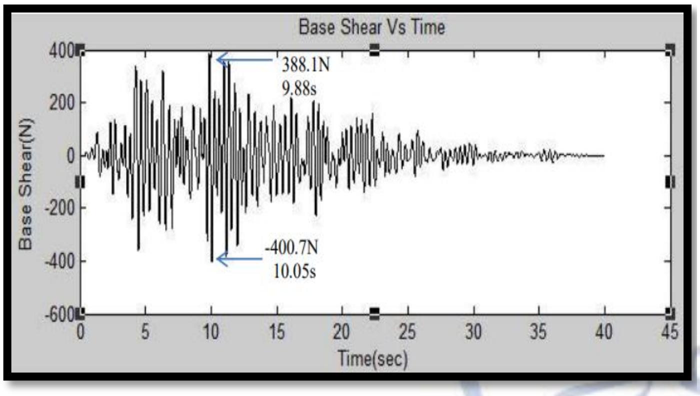
[Fig.5.1: Frequency Response analysis]



[Fig.5.2: Time History of Base Shear for 15° slope]



[Fig.5.3: Time History of Base Shear for 20° slope]



[Fig.5.4: Time History of Base Shear for 25° slope]

6. CONCLUSION

Earthquake is caused when it is subjected to the ground motion and due to which structures suffers damage and to take care of such effects it is important to know the properties of earthquake and predicts its possible response which can incur on the buildings. These properties are base shear, maximum storey displacement, velocity and acceleration, etc. In this study, such analysis has been done experimentally with validation in structural analysis tool and finite element modeling to know the response of building mentioned above. The responses for each slope angle is studied and compared.

Following conclusions can be drawn for the three sloped frame model from the results obtained in analysis:

- 15 degree sloped frame experiences maximum storey displacement due to low value of stiffness of short column while the 25 degree frame experiences minimum storey displacement.
- 15 degree sloped frame experiences nearly the same storey velocity as of 20 degree and 25 degree in the top storey but the velocity is maximum for the storey level of first floor while for 25 degree frame velocity is minimum for level of first floor.
- 15 degree sloped frame experiences maximum storey acceleration for the top floor with little variations with the 20 degrees and 25 degrees model but for the storey level of the first floor, acceleration is maximum and is minimum for the storey level of the first floor for 25 degrees frame.
- The natural frequencies of the sloped frame increases with the increase in the slope angle.
- The number of modes considered in the analysis is satisfying the codal provisions. The modal mass participation of the sloped frame model are decreasing for the first mode and increasing for the second mode with the increase in slope angle.
- For all the three frame models, time history response of the top floor acceleration is maximum at resonance condition i.e., when excitation frequency matches with fundamental frequency.
- The base shear of all the buildings are nearly the same with little variations but their distribution on columns of ground storey is such that the short column attracts the majority (75% approx.) of the shear force which leads to plastic hinge formation on the short column and are vulnerable to damage. Proper design criteria should be applied to avoid formation of plastic hinge.

FUTURE SCOPE

There is a scope for future work in this area of study. The analysis can be performed for varying frequency content i.e., for low, intermediate and high frequency content. In this study linear time history analysis is performed, one can also perform non-linear time history analysis for the sloped frame model.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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