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Dynamic Analysis of Sloped Buildings Experimental and Numerical Studies

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Abstract: *The buildings situated in hilly areas are much more prone to seismic environment in comparison to the buildings that are located in flat regions. Structures on slopes differ from other buildings since they are irregular both vertically and horizontally hence torsion ally coupled and are susceptible to severe damage when subjected to seismic action. The columns of ground storey have varying height of columns due to sloping ground. In this study, behavior 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 MATLAB platform and using 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: Ground Motion, linear time history analysis, frequency content, finite element code

1. INTRODUCTION

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 north- eastern 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 modeled 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.).

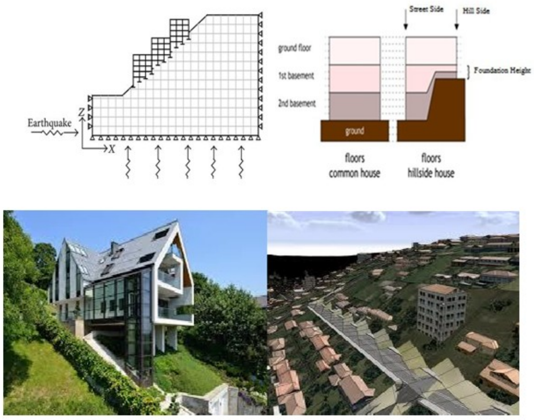


Figure 1: Buildings on sloping ground

Few research works is carried out on the seismic behaviour of structures on slopes subjected to ground motion of sinusoidal nature. Sreerama and Ramancharla (2013) studied numerically the effect on seismic behaviour on varying slope angle and compared with the same on flat ground. No work is carried out regarding the seismic behaviour of the structures on sloping ground with an experimental set up.India consists of great arc of mountains which consists of Himalayas in its northern part which was formed by on-going tectonic collision of plates. In this region the housing densities were approximately 62159 per square Km as per 2011 census. Hence there is need of study of seismic safety and the design of the structures on slopes. The response of a sloped building depends on frequency content of the earthquake as it affects its performance when it is subjected to ground motion. In this research work experimental and numerical study is done by varying sloping angle.

2. LITERATURE REVIEW

In this review, characteristics of the structures due to the variation of the slope angle are explained. Then the effect of the irregular configurations on vulnerability due to seismic forces is discussed. There are very few researchers who explained the effect of change of sloping angle.

No research work is done based on experimental investigation of the structures on sloping ground.

Seismic Behaviour of Irregular Buildings on slopes in India

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 building differ horizontally as well as vertically. Due to this irregularity the centre of mass and the centre of stiffness do not coincide to each other and it results in torsional response. The stiffness and mass of the column vary within the storey 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 analyses using IS-456 and SAP2000 and further the building is subjected and analyses 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 analyses 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 numbers of plastic hinges are more in the direction in which building is more asymmetric. Buildings 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.

3. EXPERIMENTAL MODELING

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 executed in MATLAB platform. The work performed is categorized into three sections which are as follows:-

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

Details of Laboratory Equipments

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 3.1:-

Table 3.1: Dimensions and Mass of mild steel plate

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

1. **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.
2. **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.
3. **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.

Figure 3.1: Wooden Wedge and logs

1. **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.

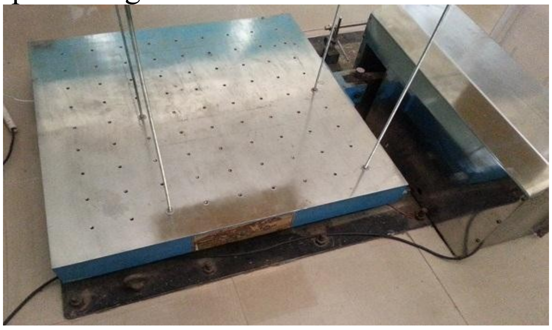


Figure 3.2: Shake Table

2. **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.

Figure 3.3: Vibration Analyzer

3. **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.

Figure 3.4: Control Panel

4. **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.

5. **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.

Figure 3.5: Accelerometer

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 NIT Rourkela.

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.

Experimental Model for 15° slope

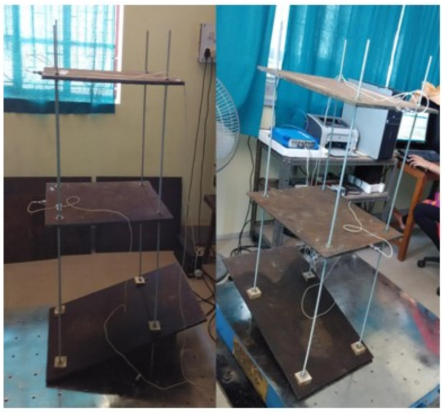


Figure 3.6: Experimental Model for 15° slope

Experimental Model for 20° slope

Figure 3.7: Experimental Model for 20° slopeExperimental Model for 25° slope

Figure 3.8: Experimental Model for 25° slope

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

During the experiment, free vibration analysis was performed for each frame model as mentioned in article 3.2.3. The first two natural frequencies obtained for two modes are shown in table 3.2.

Table 3.2: Natural frequencies of model with different slope inclinations

Type of Model	Natural Frequency (Hz)	
	Mode 1	Mode 2
15°	2.05	5.8
20°	2.2	5.945
25°	2.6	6.55

Each of the above frame model were excited with sinusoidal harmonic loading which is defined by following expression $x = x_o \sin\omega t; [\omega = 2\pi f]$ where x_o is the amplitude of excitation (mm) f is the frequency of excitation (Hz) In the above expression, the frequency of excitation is applied over a range which included the natural frequency of the model. The displacement amplitude of excitation was kept constant i.e., $x_o = 5$ mm. The maximum storey displacements obtained at resonance condition i.e., when excitation frequency matches with the natural frequency of the model for all the slope angles is shown in table 3.3, table 3.4 and table 3.5.

Table 3.3: Maximum Storey Displacements (Absolute) for frame model of 15° inclination

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

Table 3.4 : Maximum Storey Displacements (Absolute) for frame model of 20° inclination

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

Table 3.5: Maximum Storey Displacements (Absolute) for frame model of 25° inclination

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

Frequency Response Analysis

Figure 3.9 shows the response of frequency (Hz) on X-axis with Top storey displacement (mm) on Y-axis for all three slope angles. In this plot the displacement is decreasing due to the increase in frequency and slope angle and the increased stiffness of short column on hill side.

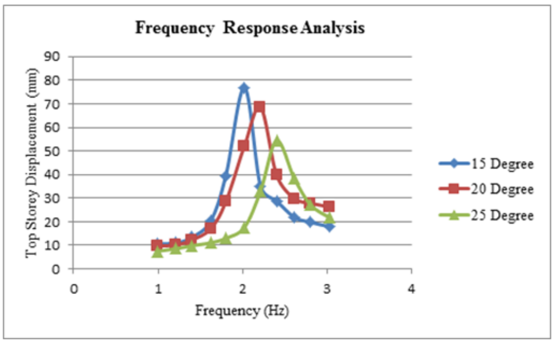


Figure 3.9: Frequency Response analysis

Figure 3.10(a) and 3.10(b) for acceleration (top storey) versus time showing the dominance of first fundamental frequency (2.05 Hz) obtained by superimposing it with the excitation frequency of value lower (1.62 Hz) than the fundamental frequency and of value higher (2.80 Hz) than the fundamental frequency. In both the plots it is observed that fundamental frequency dominates the response over the excitation frequencies of 1.62 Hz and 2.80 Hz.

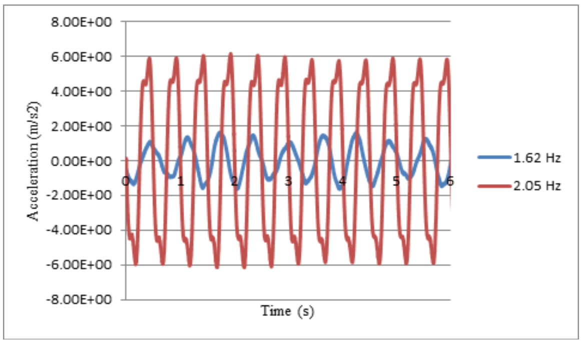


Figure 3.10(a): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 1.62 Hz and 2.05 Hz

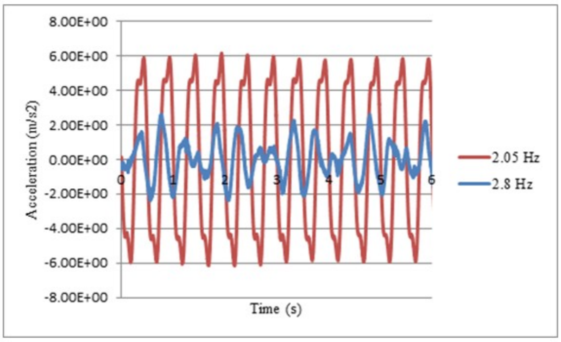


Figure 3.10(b): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 2.05 Hz and 2.80 Hz

Figure 3.11(a) and 3.11(b) for acceleration (top storey) versus time showing the dominance of first fundamental frequency (2.21 Hz) obtained by superimposing it with the forcing frequency of value lower (1.80 Hz) than the fundamental frequency and of value higher (2.80 Hz) than the fundamental frequency. In both the plots it is observed that fundamental frequency dominates the response over the excitation frequencies of 1.80 Hz and 2.8 Hz.

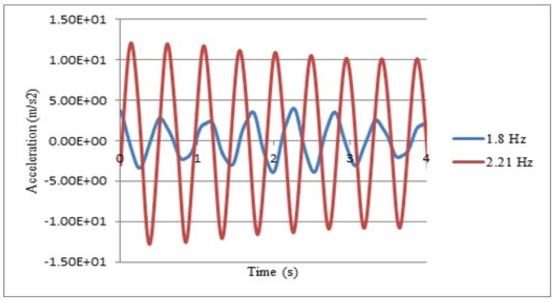


Figure 3.11(a): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 1.8 Hz and 2.21 Hz

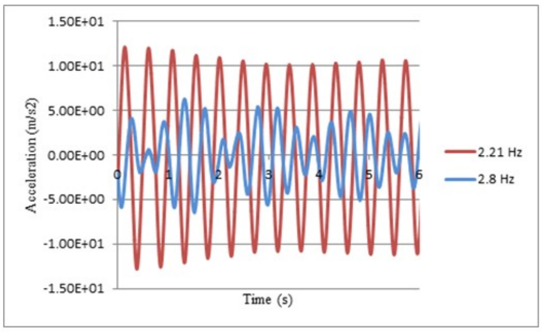


Figure 3.11(b): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 2.21 Hz and 2.8 Hz

Figure 3.12(a) and 3.12(b) for acceleration (top storey) versus time showing the dominance

of first fundamental frequency (2.6 Hz) obtained by superimposing it with the forcing

frequency of value lower (2.02 Hz) than the fundamental frequency and of value higher (2.80 Hz) than the fundamental frequency. In both the plots it is observed that fundamental frequency dominates the response over the excitation frequencies of 2.02 Hz and 2.80 Hz.

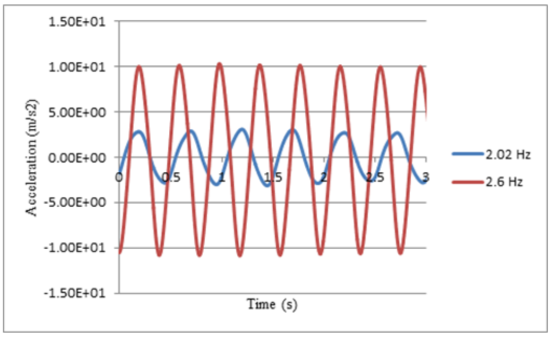


Figure 3.12(a): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 2.02 Hz and 2.6 Hz

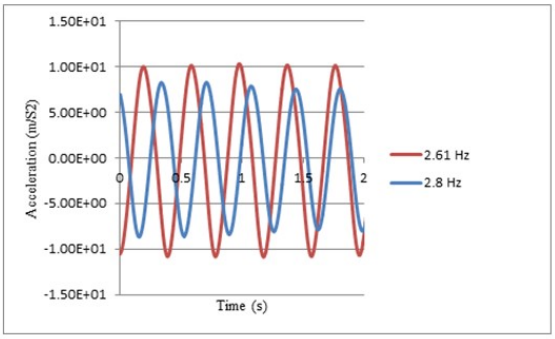


Figure 3.12(b): Time history of Top floor acceleration under sinusoidal ground motion with amplitude of 5 mm and frequencies 2.61 Hz and 2.8 Hz

5. NUMERICAL MODELING

Form the literature review we observed that there is a need to develop a Finite Element model on sloped frame to validate the results obtained from the commercial software like STAAD Pro., ETABs, and SAP 2000 etc. Therefore a finite element modeling is carried out for the forced vibration analysis. A finite element model is developed for the sloped frame and its natural frequencies are computed by conducting free vibration analysis. Forced vibration analysis is used to study the dynamic response of the frame model with the help of Newmark's integration method and the results obtained are validated with structural analysis tool i.e., STAAD Pro.

Numerical Results and Discussions

Two storied sloped frame with ground inclination of 15°

With reference to the details in the article 3.2.3 and 4.2.4.3 by performing free vibration analysis we obtained the natural frequencies of the model for two different modes shown in table 4.3:

Table 4.3: Natural Frequency of sloped frame with 15° inclination validated with Present FEM

Type of Model	Natural Frequency (Hz)	
	Mode 1	Mode 2
Experimental	2.05	5.8
Present FEM	2.2283	6.1679

Table 4.4 shows maximum storey displacement (absolute) for both experimental and finite element and STAAD Pro. model for 15° slope.

Table 4.4: Maximum Storey Displacement (mm) for Experimental, Finite Element and STAAD model

Storey No.	Maximum Storey Displacement (mm)		
	Experimental	Present FEM	STAAD Pro.
1	55.2	52.43	54.4
2	76.6	77.3	80.2

Figure 4.10 shows Maximum Storey Displacement (Absolute) vs Storey Height for experimental and numerical model.

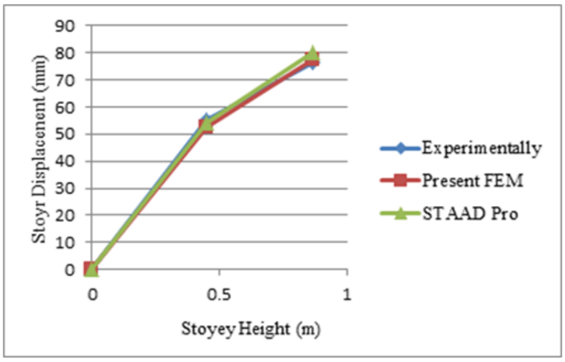
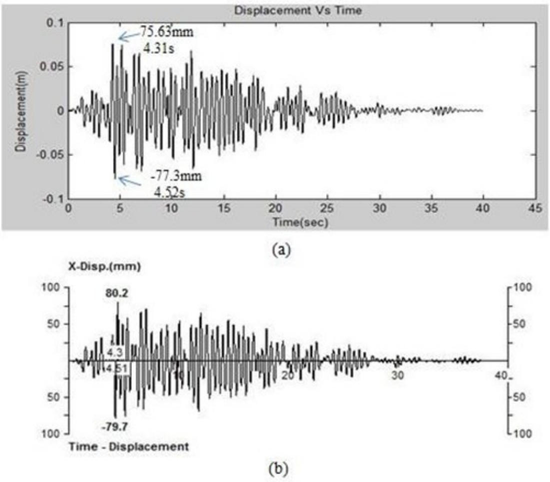


Figure 4.10: Storey Displacement vs Storey Height

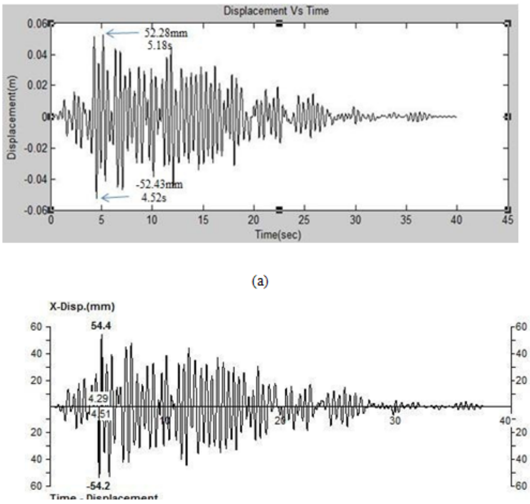
Figure 4.11 (a) and (b) and 4.12 (a) and (b) are the four plots shown for time history of top storey (roof) displacement and displacement of storey of 1st floor obtained in the numerical model i.e., Finite Element and STAAD Pro. Model.



(a)

(b)

Figure 4.11: Time History of Top storey Displacement (a) Present FEM (b) STAAD Pro



(a)

Figure 4.12: Time History of Storey (1st Floor) Displacement (a) Present FEM (b) STAAD Pro for 15° slope

Table 4.5 shows Maximum storey velocity (Absolute) for both Finite Element and STAAD Pro. model for 15° slope.

Table 4.5: Storey Velocity (mm/s) for Present FEM and STAAD model

Storey No.	Maximum Storey Velocity (mm/s)	
	Present FEM	STAAD Pro.
1	733.8	751
2	1133	1169

Figure 4.13 for Absolute Maximum Storey velocity (mm/s) vs Storey Height (m) for Present FEM and STAAD Pro model

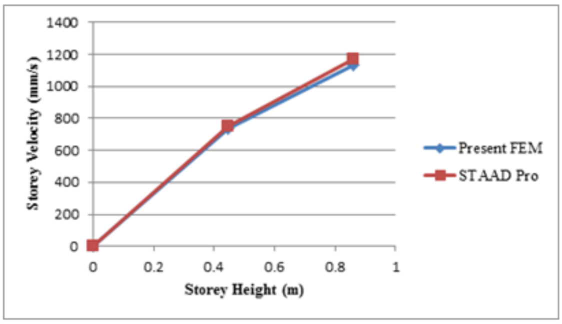
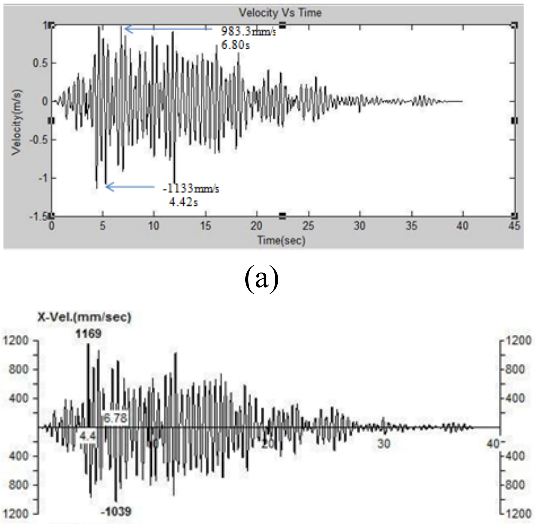


Figure 4.13: Storey Velocity vs Storey Height for 15° slope

Figure 4.14 (a) and (b) and Figure 4.15 (a) and (b) are the four plots shown for time history of top storey (roof) velocity and velocity of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



(a)

(b)

Figure 4.14: Time History of Top Storey Velocity (a) Present FEM (b) STAAD Pro for 15° slope

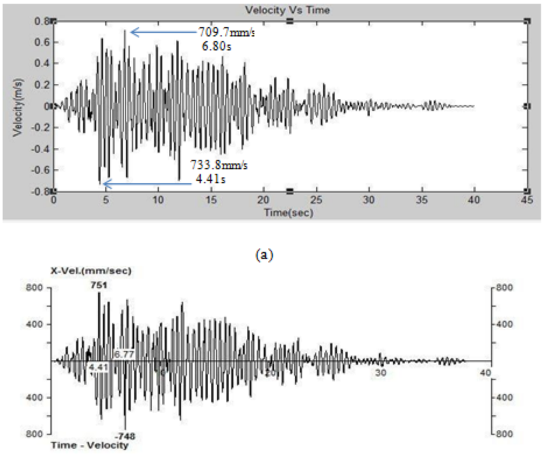


Figure 4.15: Time History of Storey (1st Floor) Velocity (a) Present FEM (b) STAAD Pro for 15° slope

Table 4.6 shows Maximum storey acceleration (Absolute) for both Finite Element and STAAD Pro. model for 15° slope

Table 4.6: Maximum Storey Acceleration (m/s^2) for Present FEM and STAAD model

Storey No.	Maximum Storey Acceleration (m/s^2)	
	Present FEM	STAAD Pro.
1	15.06	14.9
#	21.08	21.9

Figure 4.16 shows Absolute Maximum

Storey Acceleration (m/s^2) vs Storey Height (m) for Present FEM and STAAD Pro. Model

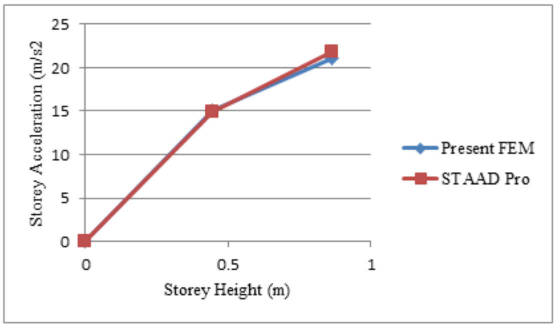
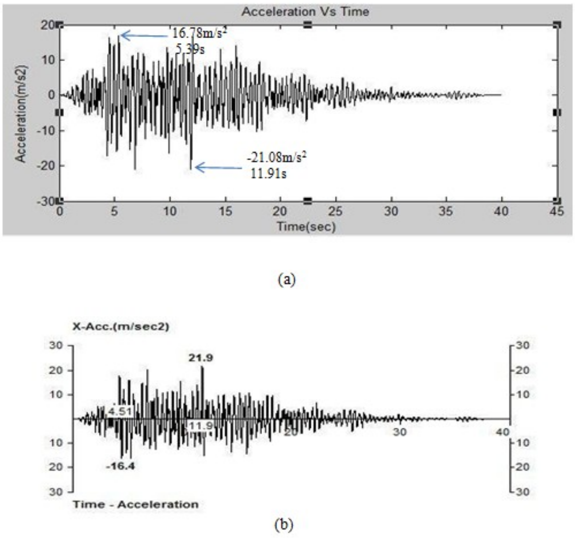


Figure 4.16: Storey Acceleration vs Storey Height

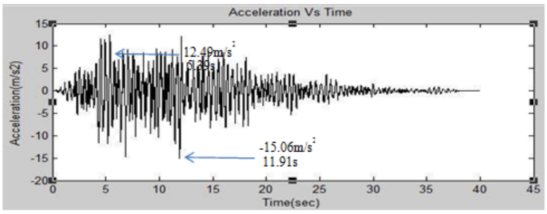
Figure 4.17 (a) and (b) and Figure 4.18 (a) and (b) are the four plots shown for time history of top storey (roof) acceleration and acceleration of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



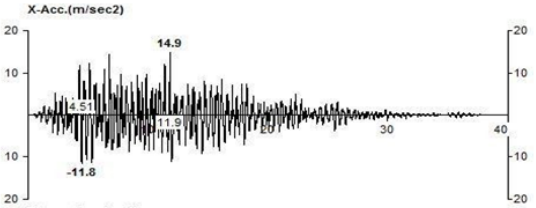
(a)

(b)

Figure 4.17: Time History of Top Storey Acceleration (a) Present FEM (b) STAAD Pro for 15° slope



(a)



(b)

Figure 4.18: Time History of Storey (1st Floor) Acceleration (a) Present FEM (b) STAAD Pro for 15° slope

Table 4.7 showing Maximum Base Shear (Absolute) (N) of frame with respect to Finite Element and STAAD Pro. model.

Table 4.7: Maximum Base Shear (N) (Absolute) for Present FEM and STAAD model

Model	Maximum Base Shear (N)
Present FEM	393.6
STAAD Pro.	389.97

Figure 4.19 shows time history of base shear for FEM model for 15° slope

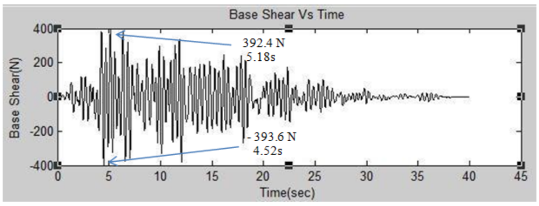


Figure 4.19: Time History of Base Shear for 15° slope

Two storied sloped frame with ground inclination of 20°

With reference to the details in the article 3.2.3 and 4.2.4.3 by performing free vibration analysis we obtained the natural frequencies of the model for two different modes shown in table 4.8:

Table 4.8: Natural Frequency of sloped frame with 20° inclination

Type of Model	Natural Frequency (Hz)	
	Mode 1	Mode 2
Experimental	2.2	5.945
Present FEM	2.38	6.303

Table 4.9 shows maximum storey displacement (absolute) for both experimental and finite element and STAAD

Pro. model for 20° slope

Table 4.9: Maximum Storey Displacement (mm) for Experimental, Finite Element and STAAD Pro. Model

Storey No.	Maximum Storey Displacement (mm)		
	Experimental	Present FEM	STAAD Pro.
1	44	44.58	46.8
2	68.3	70.57	73.7

Figure 4.20 shows Maximum Storey Displacement (Absolute) vs Storey Height for experimental and numerical model.

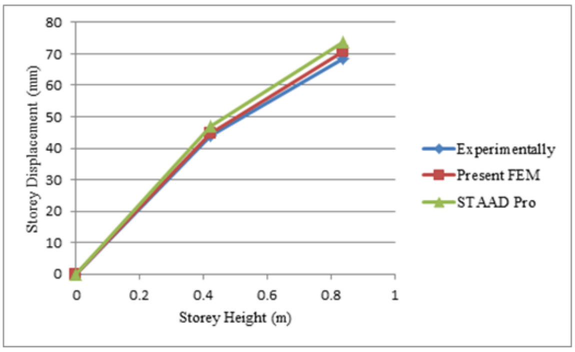


Figure 4.20: Storey Displacement vs Storey Height for 20° slope

Figure 4.21 (a) and (b) and 4.22 (a) and (b) are the four plots shown for time history of top storey (roof) displacement and displacement of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.

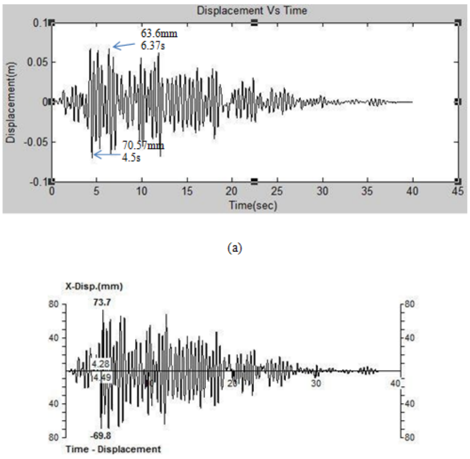


Figure 4.21: Time History of Top storey Displacement (a) Present FEM (b) STAAD Pro for 20° slope

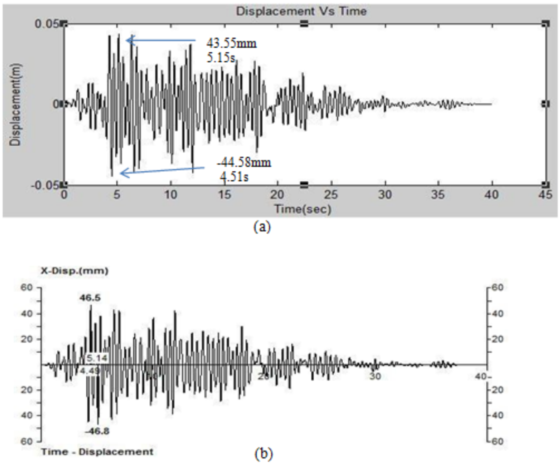


Figure 4.22: Time History of Storey (1st Floor) Displacement (a) Present FEM (b) STAAD Pro for 20° slope

Table 4.10 shows Maximum storey velocity (Absolute) for both Finite Element and STAAD Pro. model for 20° slope

Table 4.10: Maximum Storey Velocity (mm/s) for Present FEM and STAAD model

Storey No.	Maximum Storey Velocity (mm/s)	
	Present FEM	STAAD Pro.
1	720.5	697
2	1145	1134

Figure 4.23 for Absolute Maximum Storey velocity (mm/s) vs Storey Height (m) for Present FEM and STAAD Pro model

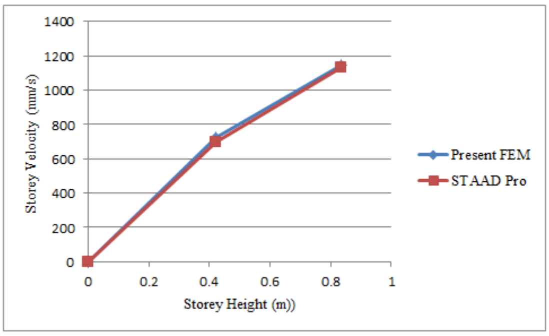
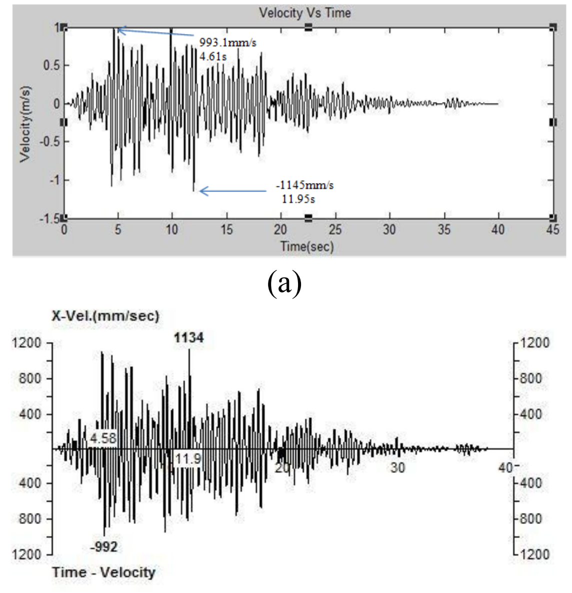


Figure 4.23: Storey Velocity vs Storey Height for 20° slope

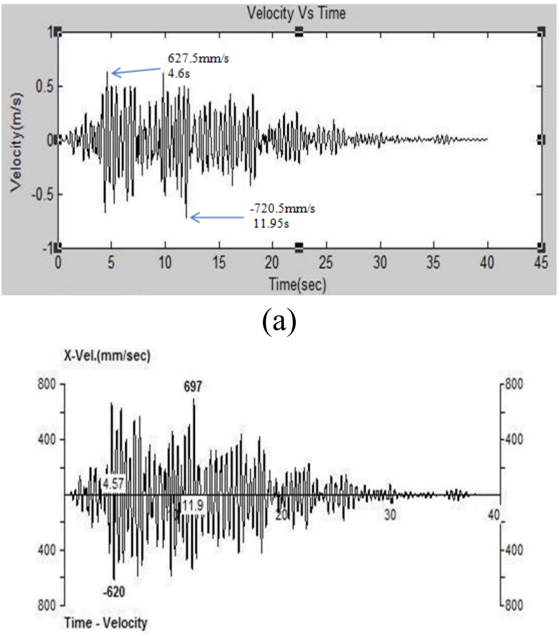
Figure 4.24 (a) and (b) and 4.25 (a) and (b) are the four plots shown for time history of top storey (roof) velocity and velocity of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



(a)

(b)

Figure 4.24: Time History of Top Storey Velocity (a) Present FEM (b) STAAD Pro for 20° slope



(a)

(b)

Figure 4.25: Time History of Storey (1st Floor) Velocity (a) Present FEM (b) STAAD Pro for 20° slope

Table 4.11 shows Maximum storey acceleration (Absolute) for both Finite Element and STAAD Pro. model for 20° slope

Table 4.11: Maximum Storey Acceleration (m/s^2) for Present FEM and STAAD model

Storey No.	Maximum Storey Acceleration (m/s^2)	
	Present FEM	STAAD Pro.
1	14.13	14.8
2	20.4	21.1

Figure 4.26 shows Absolute Maximum Storey Acceleration (m/s^2) vs Storey Height (m) for Present FEM and STAAD Pro. model

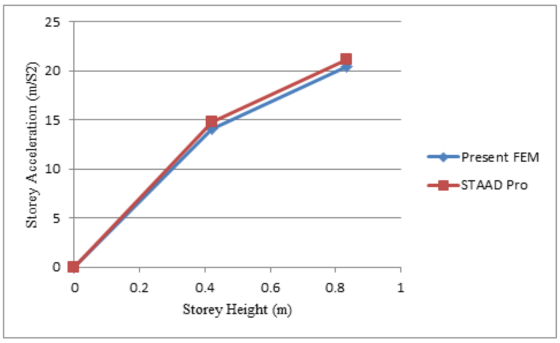
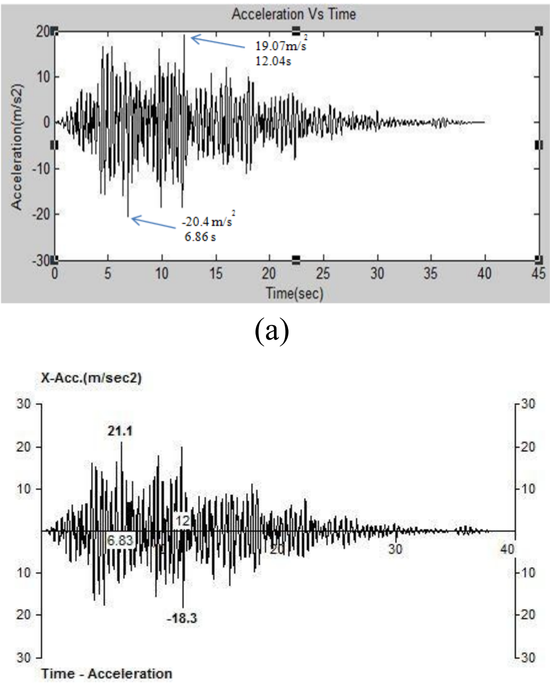


Figure 4.26: Storey Acceleration vs Storey Height for 20° slope

Figure 4.27 (a) and (b) and 4.28 (a) and (b) are the four plots shown for time history of top storey (roof) acceleration and acceleration of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model

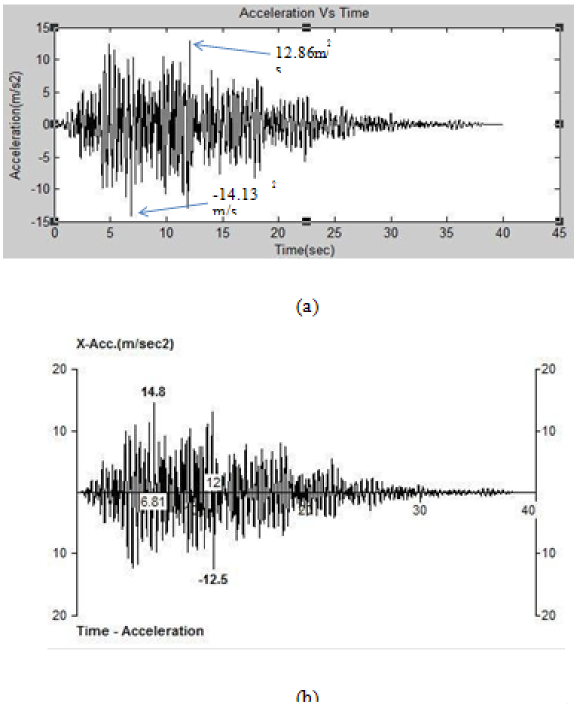


(a)

(b)

Figure 4.27: Time History of Top Storey

Acceleration (a) Present FEM (b) STAAD Pro for 20° slope



(a)

(b)

Figure 4.28: Time History of Storey (1st Floor) Acceleration (a) Present FEM (b) STAAD Pro for 20° slope

Table 4.12 showing Maximum Base Shear (Absolute) (N) of frame with respect to Finite Element and STAAD Pro. Model

Table 4.12: Maximum Base Shear (N) (Absolute) for Present FEM and STAAD model

Model	Maximum Base Shear (N)
Present FEM	400
STAAD Pro.	401.14

Figure 4.29 shows time history of base shear for FEM model for 20° slope

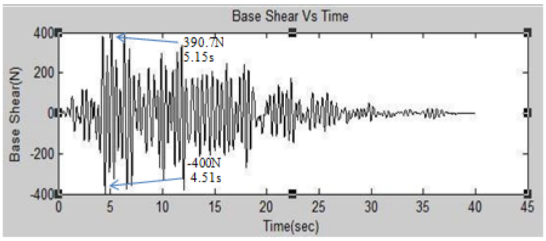


Figure 4.29: Time History of Base Shear

4.12 Two storied sloped frame with ground inclination of 25°

With reference to the details in the article 3.2.3 and 4.2.4.3 by performing free vibration analysis we obtained the natural frequencies of the model for two different modes shown in table 4.13:

Table 4.13: Natural Frequency of sloped frame with 25° inclination

Type of Model	Natural Frequency (Hz)	
	Mode 1	Mode 2
Experimental	2.6	6.55
Present FEM	2.688	6.6602

Table 4.14 shows maximum storey displacement (absolute) for both experimental and finite element and STAAD Pro. model for 25° slope

Table 4.14: Maximum Storey Displacement (mm) for Experimental, Finite Element and STAAD model

Storey No.	Maximum Storey Displacement (mm)		
	Experimental	Present FEM	STAAD Pro.
1	32.9	31.46	31.8
2	58.3	59.15	59.4

Figure 4.30 shows Maximum Storey Displacement (Absolute) vs Storey Height for experimental and numerical model.

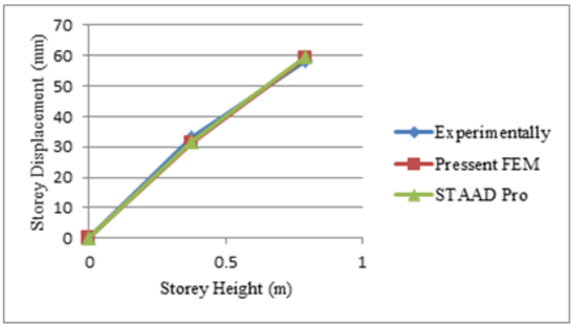
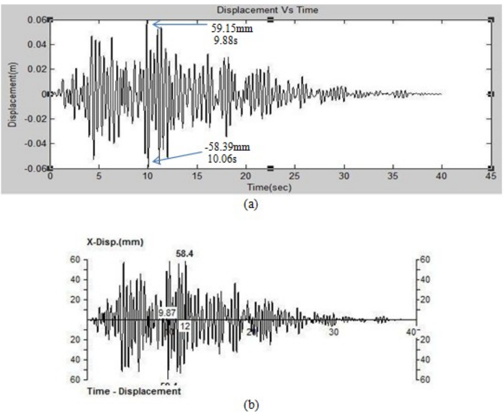


Figure 4.30: Storey Displacement vs Storey Height for 25° slope

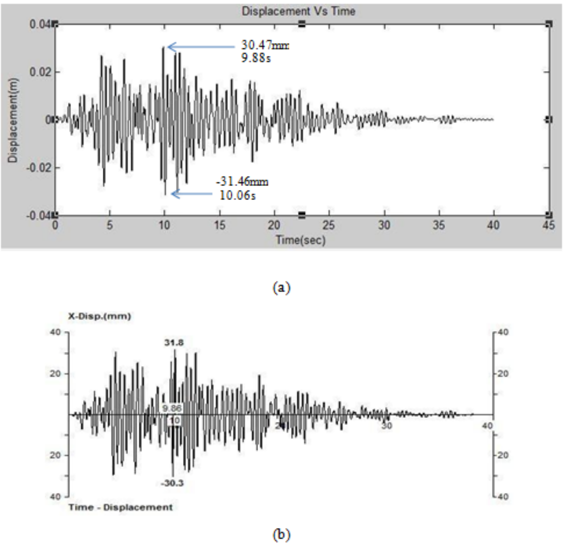
Figure 4.31 (a) and (b) and 4.32 (a) and (b) are the four plots shown for time history of top storey (roof) displacement and displacement of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



(a)

(b)

Figure 4.31: Time History of Top storey Displacement (a) Present FEM (b) STAAD Pro for 25° slope



(a)

(b)

Figure 4.32: Time History of Storey (1st Floor) Displacement (a) Present FEM (b) STAAD Pro for 25° slope

Table 4.15 shows Maximum storey velocity (Absolute) for both Finite Element and STAAD Pro. model for 25° slope

Table 4.15: Maximum Storey Velocity (mm/s) for Present FEM and STAAD model

Storey No.	Maximum Storey Velocity (mm/s)	
	Present FEM	STAAD Pro.
1	582	550
2	1146	1111

Figure 4.13 for Absolute Maximum Storey velocity (mm/s) vs Storey Height (m) for Present FEM and STAAD Pro model.

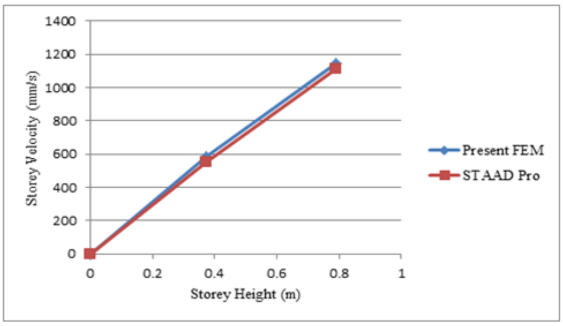
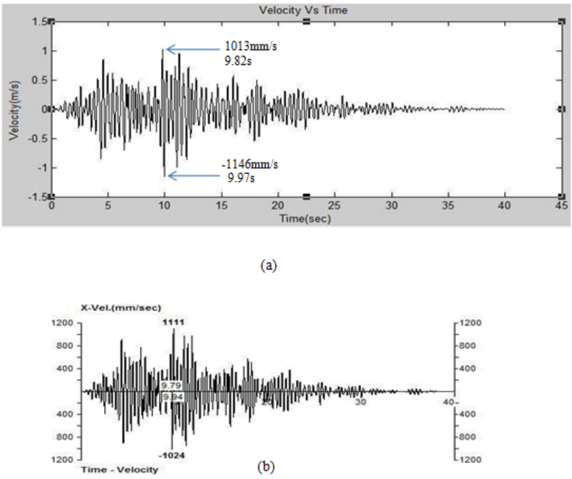


Figure 4.33: Storey Velocity vs Storey Height for 25° slope

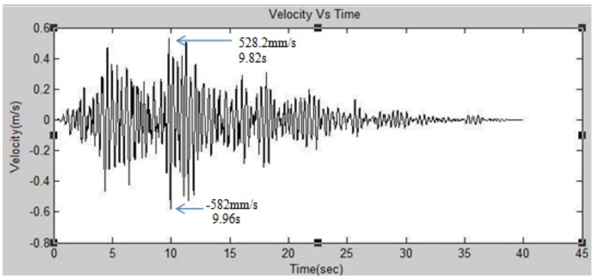
Figure 4.34 (a) and (b) and 4.35 (a) and (b) are the four plots shown for time history of top storey (roof) velocity and velocity of storey of 1st floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



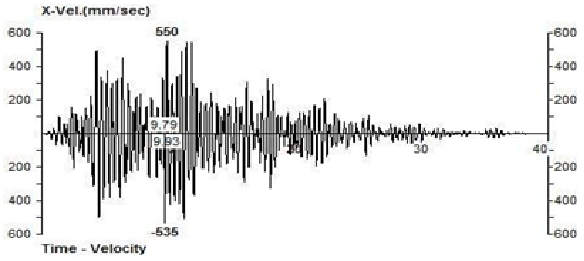
(a)

(b)

Figure 4.34: Time History of Top Storey Velocity (a) Present FEM (b) STAAD Pro for 25° slope



(a)



(b)

Figure 4.35: Time History of Storey (1^{st} Floor) Velocity (a) Present FEM (b) STAAD Pro for 25° slope

Table 4.16 shows Maximum storey acceleration (Absolute) for both Finite Element and STAAD Pro. model for 25° slope

Table 4.16: Maximum Storey Acceleration (m/s^2) for Present FEM and STAAD model

Storey No.	Maximum Storey Acceleration (m/s^2)	
	Present FEM	STAAD Pro.
1	11.57	11
2	20.67	20.5

Figure 4.36 shows Absolute Maximum Storey Acceleration (m/s^2) vs Storey Height (m) for Present FEM and STAAD Pro. model

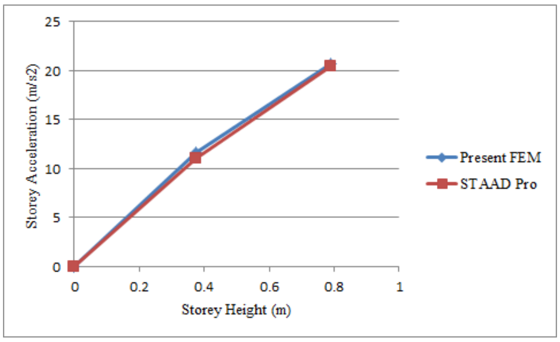
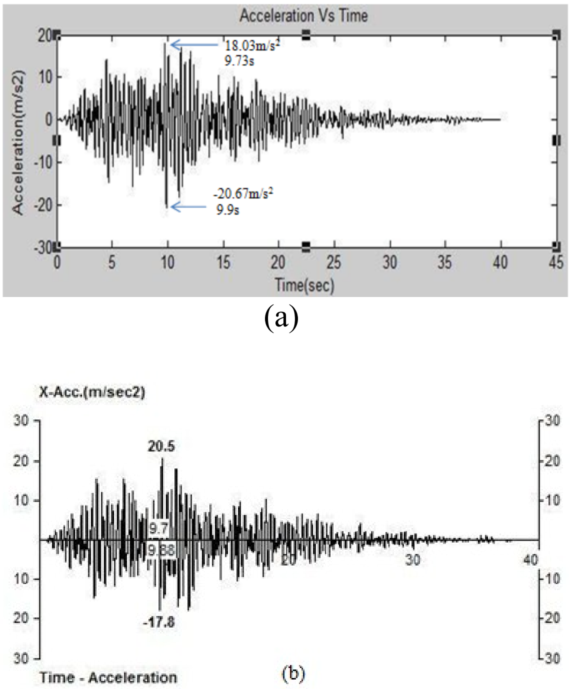


Figure 4.36: Storey Acceleration vs Storey Height for 25° slope

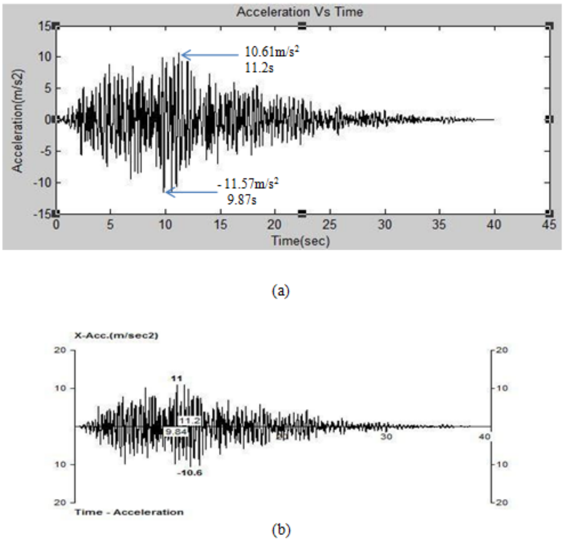
Figure 4.37 (a) and (b) and 4.38 (a) and (b) are the four plots shown for time history of top storey (roof) acceleration and acceleration of storey of 1^{st} floor obtained in the numerical i.e., Finite Element model and STAAD Pro. model.



(a)

(b)

Figure 4.37: Time History of Top Storey Acceleration (a) Present FEM (b) STAAD Pro for 25° slope



(a)

(b)

Figure 4.38: Time History of Storey (1^{st} Floor) Acceleration (a) Present FEM (b) STAADPro for 25° slope

Table 4.17 shows Maximum Base Shear (Absolute) of frame with respect to Finite Element and STAAD Pro. model

Table 4.17: Maximum Base Shear (N) (Absolute) for Present FEM and STAAD model

Model	Maximum Base Shear (N)
Present FEM	400.7
STAAD Pro.	387.21

Figure 4.39 shows time history of base shear for FEM model for 25° slope

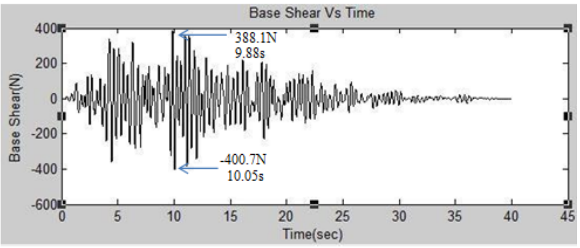


Figure 4.39: Time History of Base Shear

4.13 Mass Participation factor of both modes for considered slope angles

In the analysis of structures, the number of modes considered should have at least 90% of the total seismic mass as per IS 1893-2002 (Part I). Table 4.18 shows that the number of modes considered here are satisfying the criteria. The Mass participation factor (%) for both modes 1 and 2 and all the three slope inclination is tabulated and it is observed that the mass participation factor decreases with increase in slope inclination.

Table 4.18: Mass Participation Factor (%) of both modes for different slope angle

Slope angle	Mass Participation Factor (%)	
	Mode 1	Mode 2
15°	96.4	3.6
20°	95.08	4.92
25°	91.33	8.67

6. CONCLUSIONS

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

5.1.1 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.

5.1.2 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.

5.1.3 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.

5.1.4 The natural frequencies of the sloped frame increases with the increase in the slope angle.

5.1.5 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.

5.1.6 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.

5.1.7 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.

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