Dynamic Analysis of Sloped Building

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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 torsionally 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, behaviour of two storied sloped frame having step back configuration is analyzed for sinusoidal ground motion with different slope angles i.e., 18°, 22° and 26° with an experimental set up and 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 .

I. 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 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 18°, 22° and 26° to the ground subjected to sinusoidal ground motion is modelled with an experimental setup and design software (STAAD Pro.).

1.2 Origin of the Project

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.

1.3 Research Significance

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.

II. LITERATURE REVIEW

2.1 Overview

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.

2.2 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 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.

III. EXPERIMENT ON MODEL WITH DIFFERENT SLOPE ANGLE

This process deals with experimental works performed on free vibration and forced vibration on sloped frame model. The results obtained from the experimental analysis

3.1Details of Laboratory Equipments

A 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

Table 3.1: Dimensions and Mass of mild steel plate

Plate no	Dimension(cm)	Mass(kg)
Plate 1&2	60x50x1	19.50
Plate3	80x50x1	24.90

B.Four circular threaded rod-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 8.8 mm

C. Nuts and washers- The number of set of Nuts and washers used is 32mm. 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.

D. 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 like this arrangement

E. 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.

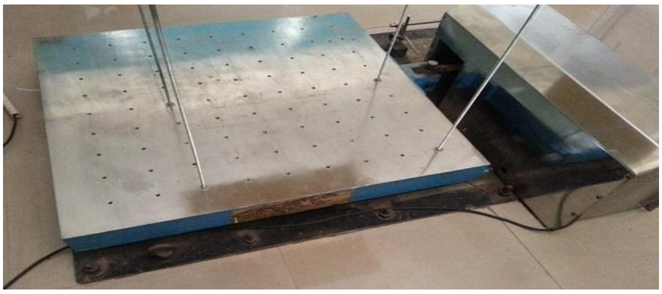


Figure3.2Shake Table

F. 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

Figure 3.3 Vibration Analyser

G. 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.

Fig 3(c)

H. 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. All the records obtained during the vibration of the model is simultaneously displayed in the monitor.

I. 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 time) but it is the acceleration which it experiences due to the free fall of an object. Accelerometer transfers its record to the vibration analyses which is received by computer and transforms it to a signal.

3.2Experimental Results and Discussions

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

Figure 3.5 Accelerometer

Table 3.2: Natural frequencies of model with different slope inclinations

Type of structure	Natural frequency of S1	Natural frequency of S2
18°	2.05	5.80
22°	2.2	5.95
26°	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 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 18° inclination

Storey No	Maximum Storey Displacement(mm)
1	59.2
2	79.6

Table 3.4: Maximum Storey Displacements (Absolute) for frame model of 22° inclination

Storey No	Maximum Storey Displacement(mm)
1	42
2	62.5

Table 3.5: Maximum Storey Displacements (Absolute) for frame model of 26° inclination

Storey No	Maximum Storey Displacement(mm)
1	30.8
2	54.2

IV. STAAD MODELING

4.1 Introduction

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 18°, 22° and 26°. 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.

4.2Frame Modeling in STAAD

In this article, modelling is done in STAAD Pro. A two storied sloped frame model with plan and elevation is shown from figure 4.2 to figure 4.7 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.

4.3 Two storied sloped frame with inclination of 18° to the horizontal

1) Plan

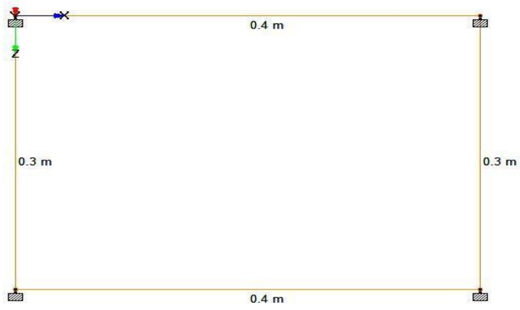


Figure 4.1: Plan of sloped frame for 18° inclination

2) Elevation

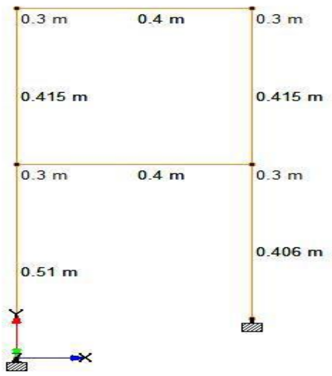


Figure 4.2: Elevation of sloped frame for 18° inclination

4.4 Loads: Uniformly distributed load of 0.5044 kN/m is applied in both longitudinal (X) direction and Y-direction at each storey level. The figure 4.8 shows front and side elevation of applied loads in X and Y directions.

The load applied is the mass of plate which is experimental model multiplied by the acceleration due to gravity i.e., 15.44*9.81=151.466 N or .151466 kN.

This value of load is uniformly distributed throughout the length of beam 0.151466/0.3=.50488 kN/m.

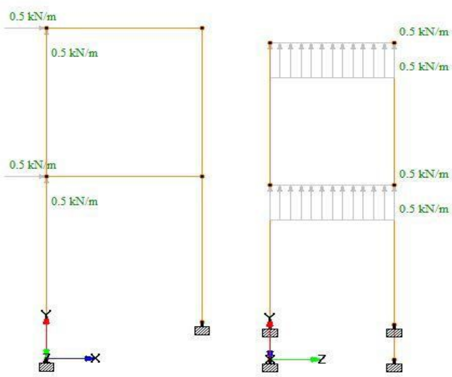


Figure 4.3: Load distribution in Longitudinal-X and Vertical-Y direction

4.5 Material Properties

The table 4.1 shows the properties of materials that are used in the modelling of structure in STAAD Pro.

Table 4.1: Steel and Column Bar Properties

Title	Steel Properties	Column Bar Properties
Modulus of Elasticity	20000 GPa	77.3 GPa
Poisons ratio (ν)	0.3	0.3
Mass Density (Kg/m3)	7720	7300
Shear modulus	7692.307 GPa	29.615 GPa

4.6 Structural Elements

*In STAAD Pro. Linear Time History Analysis is performed on above models subjected to ground motion of intermediate frequency content as per spectra of IS 1893(Part I): 2002.

*Height of storey for first and second floor is taken as 51 cm and 41.5 cm respectively.

*While the length of short column (on right) is 40.65 cm , 37.3 cm and 32 cm for slope of 18°, 22° and 26° respectively.
*The length of beam is 40 cm in longitudinal (X) direction and 30 cm in transverse (Z) direction. The details of size of beam and column are shown in table 4.2.

Table 4.2: Details of Beam and Column with length and cross section dimensions

Element	Cross Section Dimension(mm)	Length (cm)
Beam (X)	100x100	40
Beam (Y)	80x80	30
Column 1st floor	7.7	51
Column 2nd floor	7.7	41.5

4.7 Ground Motion and Time History Analysis

4.7.1 Ground Motion

It is the motion of earth's surface due to the earthquake or any explosion. It is produced due to the waves which are generated by slip of fault plane or sudden pressure at the explosive source which travel through the surface of the earth. Earthquake is a term which is used to refer sudden release of seismic energy caused by sudden slip on a fault or due to any volcanic or magmatic activity. The strain energy stored inside the earth crust is released due to tectonic movement of the plates and maximum part of it changes into heat and sound and the remaining is transforms into the form of seismic waves. Most of the earthquakes occur due to the plate tectonics. The tectonic plates are large in size thin and rigid plates that moves relative to one another on the earth's outer surface.These plates are found in uppermost part of mantle which is together referred to as lithosphere. There are seven major plates which are Pacific, American, Australian, Indian, Eurasian, African and Antarctic plates.

The main concern of Engineers is the property and nature of ground motion while the scientists and researchers are interested in the nature and property of earthquake. Engineers use accelerograph to measure the ground acceleration whereas scientists use seismograph to record the seismic waves. The seismic waves are mainly of two types i.e., body waves and surface waves. The body waves further comprises of two types which are primary waves (P-wave) and secondary waves (S-wave). The surface waves are also of two types i.e., Rayleigh and Love waves.

When the shaking of earth is strong that is close to 50 km range is referred to as strong ground motion. The motion occurs in three linear displacements and three rotational displacements. Peak ground acceleration (PGA) is the maximum absolute value of ground acceleration. The frequency content, PGA and time duration are the three most important characteristics of an earthquake. The frequency content of an earthquake is the ratio of peak ground acceleration (PGA) in terms of acceleration due to gravity (g) to the peak ground velocity (m/s) (PGV). It is classified into three high, intermediate and low frequency content.

PGA/PGV > 1.2 High Frequency Content

0.8 < PGA/PGV > 1.2 Intermediate Frequency Content

PGA/PGV < 0.8 Low frequency content

The first natural frequency (corresponding to first mode) of a structure is termed as the fundamental frequency. When the excitation frequency and natural frequency matches then the resonance occurs. Earthquake ground motion is dynamic in nature and can be classified as deterministic non-periodic transient load as well as probabilistic load.Earthquake is classified based on focal depth, location, epicentral distance, causes and magnitude. Intensity and magnitude are two specific parameters of earthquake. The intensity of earthquake is measured by the severity of shaking of ground at a certain location. It is a qualitative measure of an earthquake and is measured by MM scale (Modified Mercalli) scale. Magnitude is the amount of seismic energy released at the source of earthquake. It is a quantitative measure of an earthquake which is determined by Richter magnitude scale. For a particular earthquake the magnitude is constant irrespective of its location but its intensity varies from one location to another. Figure 4.9 shows the variation of ground acceleration with time. The duration of ground motion is 40 seconds and its peak value is -1.0g which occurs at time t=11.90 seconds.

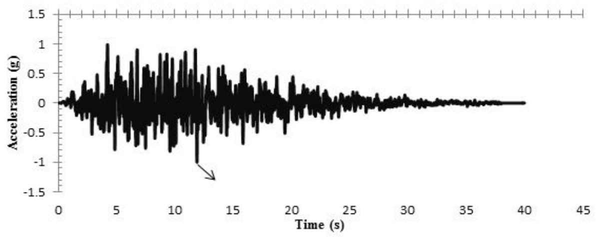


Figure 4.4: Compatible Time History as per spectra of IS 1893 (Part1):2002 for 5% damping at rocky soil

4.7.2 Time History Analysis

Structural analysis deals with finding out physical response of a structure when subjected to any action (force). This action can be static or dynamic. If the action is constant for a span of time then it is termed as static and if it varies fairly quickly then it is termed as dynamic. The study of response of the structure subjected to dynamic loading is called as structural dynamics. Ground motion comes under type of dynamic loading. Dynamic analysis is also related to inertial forces developed when the structure is subjected by suddenly applied loads for example wind blasts, explosion and earthquake.

Time history analysis is the dynamic response of a structure applied over the increment of time steps as a function of acceleration, force, moment or displacement. It provides the response under the loading which varies according to specified time function. The closer spacing of interval the greater is the accuracy achieved. This method is considered to be more realistic compared to response spectrum method. This method is useful for tall or high rise structures i.e., flexible structures. In linear dynamic model, structure is modelled with linear elastic stiffness matrix and equivalent damping matrix for multi degree of freedom structure. The main advantage of linear dynamic method over static method is that higher modes can also be taken into account.

In this study linear time history dynamic analysis is carried out to see the response of a two storied building. STAAD Pro.8 platform is used to perform the analysis. The structure is subjected to ground motion record [IS 1893 (Part1):2002 (Artificial ground motion)] compatible to time history of acceleration as per spectra of IS 1893 (Part1) for structural design in India (Refer figure 4.9: Time History of Ground Acceleration).

V. RESULTS AND DISCUSSIONS

In this chapter, the response of the structure subjected to ground motion and the results for two storied sloped building with ground inclination of 18°, 22° and 26° in terms of roof displacement, roof velocity and roof acceleration and base shear are presented. Also the storey displacement, story velocity and story acceleration for each inclination is illustrated. The responses due to ground motion as per spectra of IS 1893 (Part 1):2002 are shown. The results obtained based on experiment studies are shown with validation with experimental model.

5.1 Two storied sloped frame with ground inclination of 18°

With reference to the details in the article by performing free vibration analysis we obtained the natural frequencies of the model for two different modes shown in table 5.1:

Table 5.1: Natural Frequency of sloped frame with 18° inclination validated with Present FEM

Type of Model	Natural Frequency (Hz) of Model 1	Natural Frequency (Hz) of Model 2
Experiment	2.05	5.80
STAAD Pro	2.2283	6.167

Figure 5.1 shows Maximum Storey Displacement (Absolute) vs Storey Height for experimental and numerical model.

Table 5.2 :maximum storey displacement (absolute) for both experimental and STAAD Pro. model for 18° slope.

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

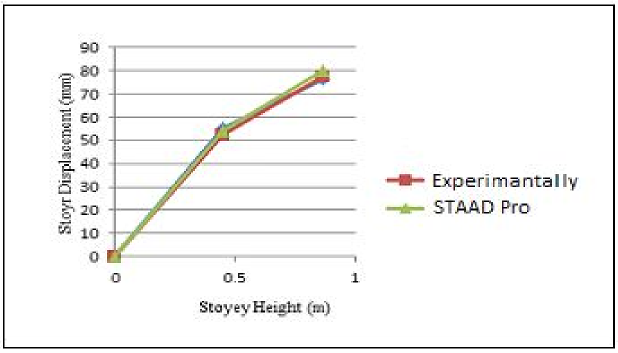
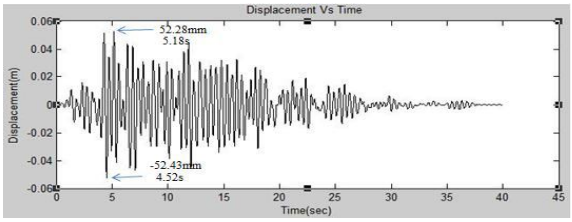


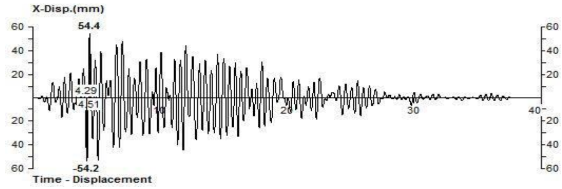
Figure 5.1: Storey Displacement vs Storey Height

Figure 5.2 (a) and (b) and 5.2 (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 Experimental and STAAD Pro. Model.



(a)

Figure 5.2: Time History of Top storey Displacement (a) Experimentally (b) STAAD Pro



(b)

Figure 5.2: Time History of Storey (1st Floor) Displacement (a) Experimental (b) STAAD Pro for 18° slope

5.2 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 5.3: Mass Participation factor (%) of both modes for different slope angle.

Slpoe Angle	Mass Participation Factor (%)	
	Mode 1	Mode2
18°	96.40	3.60
22°	95.08	4.92
26°	91.33	8.67

VI. CONCLUSIONS

6.1 Summary

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 to know the response of building mentioned above. The responses for each slope angle is studied and compared.

6.2 Conclusions

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

1. 18 degree sloped frame experiences maximum storey displacement due to low value of stiffness of short column while the 26 degree frame experiences minimum storey displacement.
2. 18 degree sloped frame experiences nearly the same storey velocity as of 22 degree and 26 degree in the top storey but the velocity is maximum for the storey level of first floor while for 26 degree frame velocity is minimum for level of first floor.
3. 18 degree sloped frame experiences maximum storey acceleration for the top floor with little variations with the 22 degrees and 26degrees 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 26degrees frame.
4. The natural frequencies of the sloped frame increases with the increase in the slope angle.
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.
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.

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