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Effect of Slope Angle Variation on The Structures Resting on Two-way Sloping Ground in Hilly Region Under Seismic Excitation

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Abstract: The building structures situated in hilly areas are much more prone to seismic environment in comparison to the buildings that are located in flat regions due to irregularities in plan as well as elevation. Structures on slope differ from other buildings since they are susceptible to severe damage when subjected to earthquake excitation. The columns have varying height due to sloping terrain. Structures may be analyzed under earthquake loadings, with or without considering the effect of soil structure interaction (SSI). In this present study, an attempt has been made to study the effect of slope angle (viz. 30°, 45°) variation for the structures resting on two-way sloping terrain, considering fixed base structures. The configuration as step back-set back building structures with plan regularity & irregularity has been adopted. This study has also evaluated the behavior or the overall performance of those structures in terms of dynamic characteristics like Fundamental time period, Base shear, Storey drift. The analysis is performed in Linear static method or Equivalent Static Frame Method (ESFM), Linear dynamic method or Response Spectrum Method (RSM), Nonlinear Static Method (NLSM) or Pushover Analysis and Nonlinear Time History Method (NLTHM). Results expose the vulnerability and also show more efficient structure between the aforesaid building structures associated with increment of slope angle in two-way sloping ground.

***IndexTerms* - Building Structures, Sloping Terrain, Irregularity, Equivalent Static Frame Method, Response Spectrum Method, Pushover Analysis, Nonlinear Time History Method**

I. INTRODUCTION

Earthquakes are very devastating for their unpredictability and its destructive power. The occurrence sometime exhausts human lives and properties due to the wrecking of structures. When a sudden structure may collapse during severe earthquakes, then it puts the human existences in danger. Over the past few decades, numerous research projects have been carried out globally to examine the causes of failure of various types of buildings under strong seismic excitations. The recent disastrous earthquake's massive devastation of both high-rise and low-rise buildings is evidence that such an examination is urgently needed in emerging nations like India. Hence, seismic behavior of asymmetric building structures has become a topic of worldwide active research. To determine the reason why such structures are so vulnerable to earthquakes, numerous investigations on the elastic and inelastic seismic behavior of asymmetric systems have been carried out. In this paper, multi-storied step back-setback buildings located in zone V of medium soil sites has been analyzed by Linear Static and Linear Dynamic method given in Indian code and evaluated using pushover analysis as per the procedure prescribed in FEMA-356.

Due to the scarcity of flatlands, construction on sloping land is becoming more and more common in mountainous areas. Due to challenges faced during project execution, both for the structure and the soil, this has presented a significant problem for structural engineers with regard to structure design. No Indian standard codes apply to construction on sloped ground in India. However, hilly areas are vulnerable to landslides; the risk is comparable to that of an earthquake. The structures may sustain significant damage if a sizable amount of earth moves quickly. Moreover, due to the rising rates of population growth in some cities in India, there is a demand of constructing buildings with multiple floors. In addition, constructing on sloping terrain is being considered more and more, mostly because there aren't enough level areas for construction. Financial development and quick urbanization in these sloping areas have been quickened because of the land improvement. As a result, population density has greatly increased, and in the hilly areas, the ratio of available to needed land is out of balance. As a result, multi-story building construction has become more common on hill slopes.

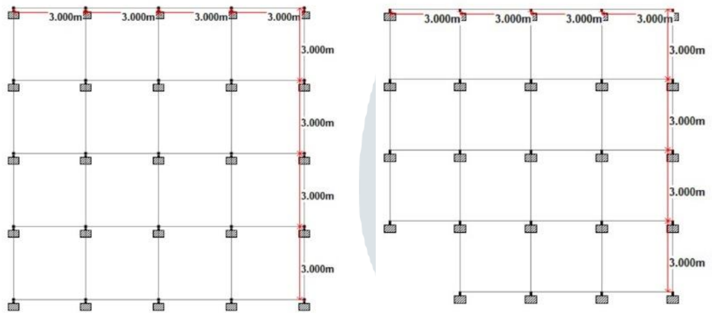
Figure 1 Buildings on sloping ground

II. RESEARCH METHODOLOGY

All the models are going to be analyzed in linear static method which is known as ESFM, linear dynamic method or Response Spectrum Method, which is known as RSM, Nonlinear time history analysis method i.e., NLTHM and NLSAM, which is known as pushover analysis. Linear analysis and nonlinear analysis both have been performed with STAAD.pro software but also SAP2000 analysis tool has been used for static nonlinear analysis i.e., pushover analysis. Default nonlinear hinges has been assigned in columns and beams as per American Society of Civil Engineers, ASCE/SEI 41–13 (2014) or Federal Emergency Management Agency, FEMA-356 (2000) for the study of pushover analysis. ESFM analysis and RSM analysis have been carried out and results have also been compared to study the seismic behavior of the structures. In modal analysis, mode shapes are generally obtained in normalized form, for that the results of response spectrum method need to be properly scaled. Scaling has been done by equating the base shears obtained from ESFM and RSM as per IS-1893 (2002) in the current study. In the ESFM (equivalent static method) analysis, different combinations of loads like dead load (DL) and earthquake load (EL) as suggested in IS 1893 (2002) have been created and the combination 1.5 (DL ± EL) has shown the maximum effect. For time history study, real time data from the Kobe earthquake are used.

DETAILS OF BUILDING AND MODELLING OF STRUCTURES

Four-storey (G+3) residential building of 12-m height with 2-m foundation depth and 12 m×12 m square regular plan with 4 nos. of bay, & L-shaped irregular plan also along with 4 Nos. of bay (shown in figure) is considered for analysis. The plan & models in different slopes of the building are shown in the Figs. A and B.
Seismic design data are as follows:
Seismic zone: IV, zone factor (Z): 0.24, soil type: Hard soil. Damping ratio: 5%, frame type: special moment resisting frame, response reduction factor (R): 5, Importance factor (I): 1.
Material properties are taken as, unit weight of concrete:25 kN/m^3, characteristic strength of concrete: 30 MPa, characteristic strength of steel: 415 MPa.
Structural elements are, beam: 250 mm×400 mm, column: 350 mm×350 mm, slab thickness: 125 mm, parapet height: 1000 mm. The bare frame structure will be considered.
The types of loads considered during the analysis are
Dead loads (DL) of beams, columns, slab,
Live load (LL) of 3 kN/m^2 at floors and 1.5 kN/m^2 at roof,
mass source (1DL+0.25LL).



A) Regular **B) Irregular**

Figure 2 2D plan of the building structures

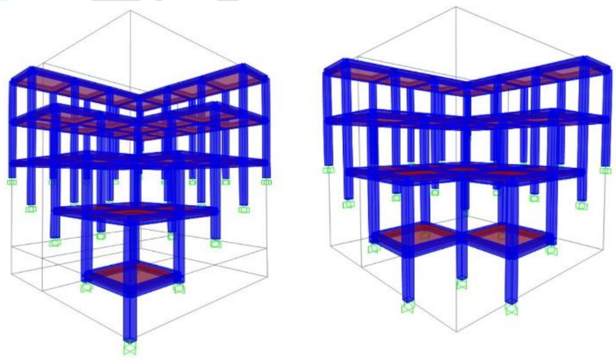


Figure 3 3D modelling of the building structures

DESCRIPTION OF MODELS

Total 4 Nos. of bare frame models are studied with regularity & irregularity. Models are considered on the 30° and 45° slopes, respectively, without SSI considerations. Descriptions and names of the models are summarized below;

Table 1 Description of different building models

SI. No.	Name of the models	Description of the models
1.	IR-30	Bare frame model with fixed base in 30° slope
2.	R-30	Bare frame model with fixed base in 30° slope
3.	IR-45	Bare frame model with fixed base in 45° slope
4.	R-45	Bare frame model with fixed base in 45° slope
Note: IR-(Irregular) & R-(Regular)		

III. RESULT & DISCUSSION

However, we have initially discussed about the thesis objective & done further work as per plan by modelling and analysis of those selected kind of building structure in slope region. The results are obtained through which we can have discuss the dynamic parameters of the structure which is under seismic excitation or can evaluate the performance of the structure in the slope or hilly region. The behavior of those structures during seismic excitation and all results are being discussed consecutively. The ESFM and RSM analysis results for different models are being discussed here under, considering different parameters are initially compared and effect of slope angle variation has been explored. Time history analysis results and results of pushover analysis would be submitted thereafter.

NATURAL TIME PERIOD

The base of a building moves with the ground when the ground is shaken, and the buildings swing back- and-forth, the time taken (in seconds) for each complete cycle of oscillation is the same and it is called Fundamental time Period (T) of the structure. Fundamental natural time period of the models has been presented in Fig. 4. The differences of percentage of time periods due to implementation of slope angle variations are given in Table 2. Generally, it has been noticed that with the increment of the slope, the fundamental time period of the models got reduced in the structures with one-way sloping condition. The structural stiffness increased due to reduction in column length; time period reduction as a result. In the previous research, the models on 45° slope have shown marginal increase of time period compared to the models on 30° slope.

In this research paper, the two-way slope angle as well as rigid foundation models have been considered. The building models have intermediate column length (in between 0 and 12 m) in different storey levels along the storey height, which does not allow the building storeys to oscillate freely as a complete storey. The intermediate columns could provide excess stiffness to those storeys and could reduce the time period of those models. However, it has been observed that without SSI consideration, models with regularity in plan, have more time period than the models in irregular building plan (IR-30, R-30 & IR-45, R-45) within the same slope angle.

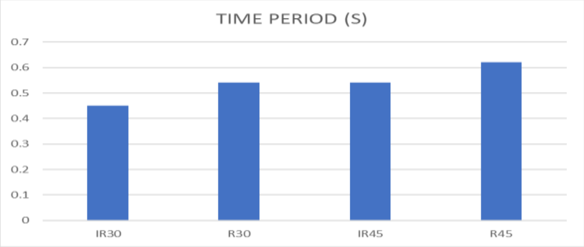


Figure 4 Fundamental time periods of models

Table 2 Percentage (%) variation of time periods

Description	Name of the models	Percentage (%)
Percentage increment of time period within same sloping angle for different kinds of building	R-30 R-45	20% 14.81%
Percentage increment of time period with increment of sloping angle for same kind of buildings	IR-45 R-45	20% 14.81%
Note: IR-(Irregular) & R-(Regular)		

BASE SHEAR

Spectral acceleration concludes the function like base shear, which depends on mass and stiffness of the structure, and these are presented in Fig. 5 Base shear is increased with increment of slope due to increased spectral acceleration and reduced time period. As we have already shown that there are two types of building, resting on two-way slope of different angle have been considered for analysis in this paper. One is step back-setback regular building structure in plan and another is irregular building structure respectively. In this case of 30° slope, it is being shown the similar ups & downs apparently in the ESFM and RSM analysis for the base shear case of study. There is an increment in base shear in regular building at 45° slope than irregular one at ESFM method. But in the RSM method, there is a marginal decreasing in base shear in regular building i.e., vice-versa. However, in the same sloping angle with horizontal, the irregular building structures shown less base shear than regular buildings due to area reduction in irregular building than the other one in ESFM. Table 3 shows the percentage floor area reduction with increasing slope angle and decreasing base shear.

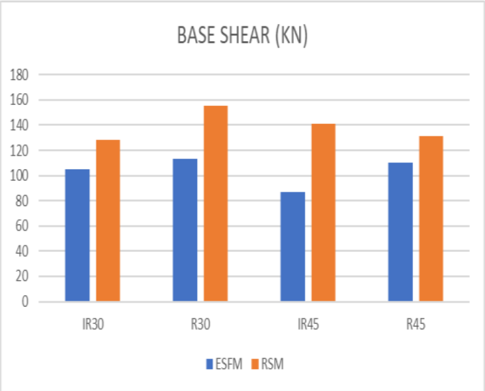


Figure 5 Base Shears of models

Table 3 Percentage (%) variation of base shears due to slope angle variation

Method	Description	Name of the models	Percentage (%)
ESFM	Percentage increment of base shear within same sloping angle for different kinds of building	R-30 R-45	7.61% 26.43%
	Percentage reduction of base shear with increment of sloping angle for same kind of buildings	IR-45 R-45	17.14% 2.65%
RSM	Percentage increment of base shear with different sloping angle for different kinds of building	R-30 IR-45	21.1% 26.43%
	Percentage reduction of base shear within same sloping angle for same kinds of building	R-45 R-45	7.09% 15.48%
	Note: IR-(Irregular) & R-(Regular)		

STOREY DISPLACEMENT

Storey drift or Displacement of the building storeys in major direction (*X* direction) and minor direction (*Z* direction) of force, with the storey height for different kinds of model in ESFM and RSM are shown in Fig. 6 to 9. In earlier studies, displacements in the force's direction (the X direction) grew with storey height and shrank with increasing slope under one-way sloping conditions. In the ESFM method of current study, displacements in the direction of force i.e., X as well as Z direction, increased along the storey height in irregular types of building structure with the increment of the slope. But the lesser drift of storeys has been found in Regular kinds of building structure with the increment of slope in two-way sloping condition. Overall displacement is less in the Regular kinds of building structure in ESFM method. However, in the RSM method of current study, displacements in the direction of force i.e., X and Z direction, increased along with the storey height but comparatively decreased with the increment of slope angle in irregular types of building structure. the drift of storeys has been found decreased in Regular kinds of building structure with the increment of slope as well in two-way sloping condition. Top storey drift has been decreased in 30° slope in both regular & irregular buildings. Overall displacement is lesser in the Regular kinds of building structure in RSM method also. For models resting on two-way sloping terrain, unidirectional displacement (X or Z direction) and unidirectional force (in X or Z direction) are observed. The taller side storey displacement of the models has been observed larger in comparison of the shorter side of the model, whichever taller side on the lower level of slope is more flexible than the shorter side at the upper level of the slope.

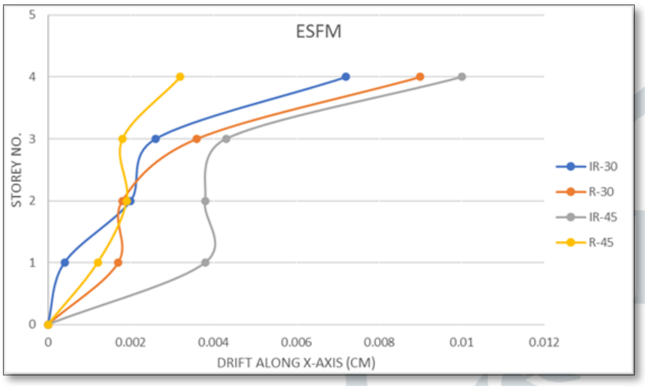


Figure 6 Displacement of models at X direction in ESFM(A).

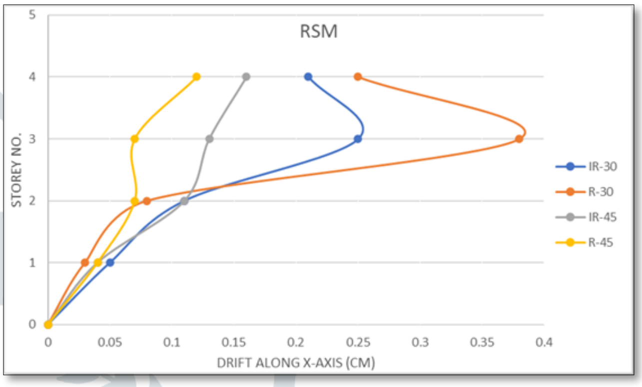


Figure 7 Displacement of model at X direction in RSM (B)

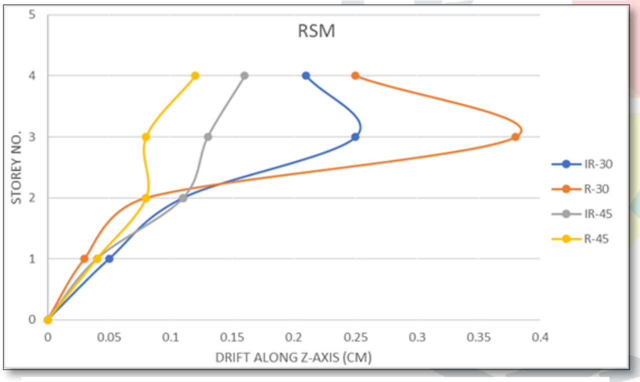


Figure 8 Displacement of models at Z direction in ESFM (C)

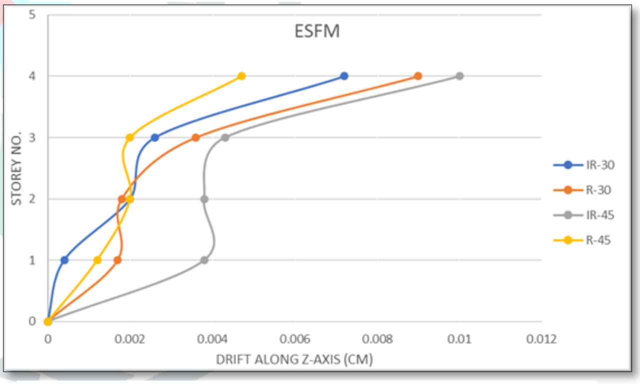


Figure 9 Displacement of models at Z direction in RSM (D).

COLUMN BENDING MOMENT

The columns are situated in the mid of the building structure running along the two-way sloping junction are being considered for the checking & analysing bending moment for the respective structures. The reason behind selecting the mid-diagonal columns is the dissimilarity of the column height in different level from other columns of the structure which could be analyzed better for result. The central diagonal panel of columns is selected for presenting variation of column bending moments of every model, which is shown in Fig. 10 & 11 respectively. In the both ESFM & RSM method, for both regular & irregular kinds of building structure, it is being observed that the bending moment of the columns laid on mid-diagonal portion of the building, is reduced with the increment of the slope angle. The columns resting on the upper side of the slope of all structures consist their maximum bending moment. In the models for slopes of 30° and 45°, the shorter side of the structure's columns at the higher level of the slope experience a higher bending moment than the taller side's columns at the lower level of the slope. Therefore, in models standing on sloping ground, there is a considerable range in column forces within a specific storey, and the columns with stronger bending moments at the upper story side of the slope are badly affected by earthquakes. Slope angle variation results in the formation of intermediate column lengths (in between 0 and 12 m) at different storey level of models resting on 30° and 45° slopes. When compared to full-length columns, these shortened columns have greater bending moments. Bending moment variation of columns in different buildings in different slope angle is presented in Table 4. Results indicate that the bending moment decreased with the increment of the slope in all buildings with step back-set back building configuration resting on two-way sloping ground.

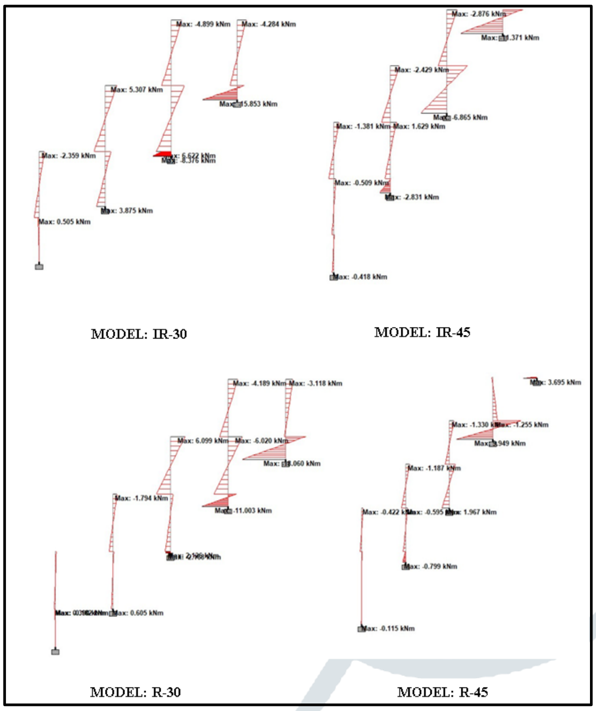


Figure 10 Column bending moment of models in ESFM method

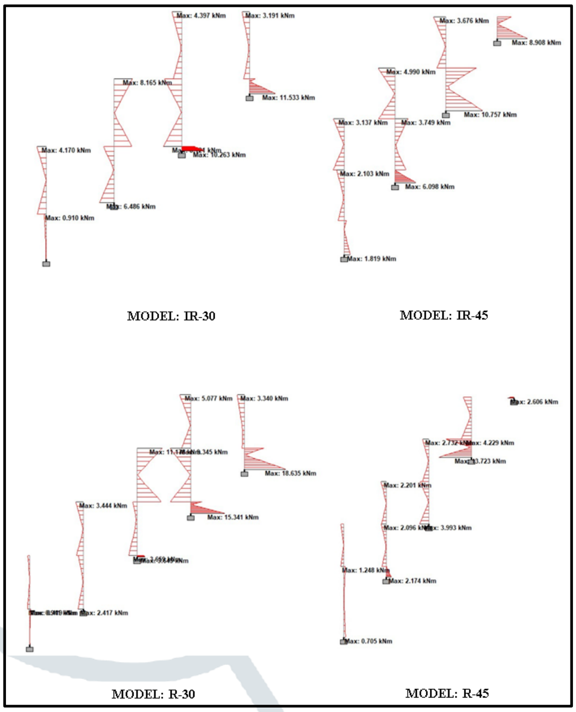


Figure 11 Column bending moment of models in RSM method

Table 4 Variation in bending moment of columns due to variation of slope angle

Description of models	Maximum bending moment of columns	
	ESFM	RSM
IR-30	15.85	11.53
IR-45	11.37	10.75
R-30	18	18.63
R-45	9.96	13.72
Note: IR-(Irregular) & R-(Regular)		

RESULT OF PUSHOVER ANALYSIS

The nonlinear static analysis or pushover analysis is performed and reviewed both by displacement control technique in capacity spectrum method as well as coefficient method, as per guidelines of Applied Technology Council, ATC-40 (1996) & Federal Emergency Management Agency, FEMA-356 (1999). In the Capacity Spectrum method, as per ATC-40, the capacity spectrum of the structure and demand curve, generates in a spectral displacement versus spectral acceleration domain. The base shear vs roof displacement curve, also known as the capacity curve or pushover curve, is what makes up a capacity spectrum, and it is plotted in the spectral displacement against spectral acceleration domain. The performance point (PP) is the location where the displacement demand curve and the structure's capacity curve converge. under earthquake loading, performance point defines the overall performance of the structure. Whether the coefficient method, as per FEMA-356, is to find target displacement which is the maximum displacement that the structure is likely to be experienced during the design earthquake. Through the use of a bilinear capacity curve representation and a number of modification factors, or coefficients, it offers a numerical method for predicting the displacement demand on the structure.

The static pushover curves of all the models in both directions are shown in Fig. 12 & 13. The displacement and base shear values at performance point of view as well as target displacement point are given in Table 5. As the capacity curve of the models crosses the displacement demand curve, well outside the linear range (at PP), in the nonlinear stage with a significant displacement value, pushover curves show the susceptibility of all models. According to the capacity spectrum approach, the starting stiffness of the models increased as well as the displacement decreased for both regular and irregular structures, and this resulted in a minor rise in base shear carrying capacity with the increment of slope angle. On the other hand, in the coefficient method, marginal increase in base shear and the target displacement noticed for irregular building structure with increment of slope, but the base shear and displacement reduction with increment of slope angle has been obtained in regular kind of structure probably due to marginal increase of time period and a bit of floor area reduction in two-way sloping ground.

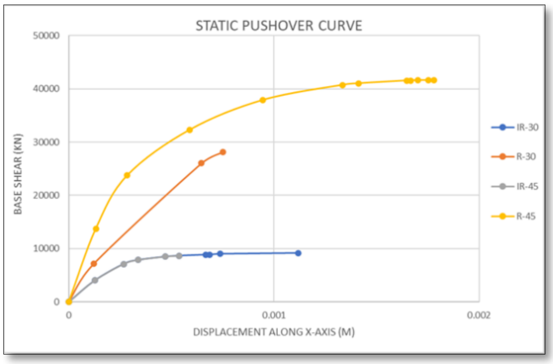


Figure 12 Static non-linear pushover curve along

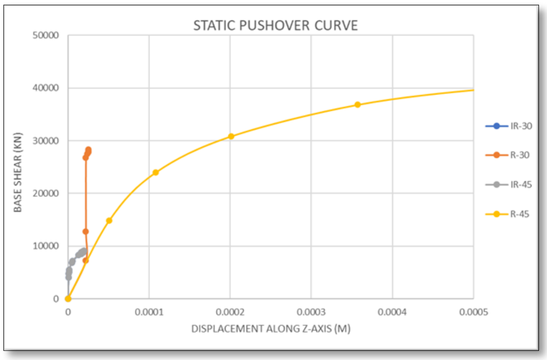


Figure 13 Static non-linear pushover curve along Z-axis

Table 5 Variation in base shear & displacement in ATC-40 & FEMA-356

Models	Capacity spectrum method		Coefficient method	
	Displacement (m)	Base shear (KN)	Displacement (m)	Base shear (KN)
IR-30	0.0032	589.94	0.005	909.14
IR-45	0.0031	595.90	0.004	919.15
R-30	0.118	225.52	0.005	1629.63
R-45	0.0005	271.15	0.002	612.17
Note: IR-(Irregular) & R-(Regular)				

RESULT OF NONLINEAR TIME HISTORY ANALYSIS

Dynamic nonlinear analysis or Nonlinear time history analysis, which experiences more accurate responses of the structures, has been performed for all the models by direct integration technique, using the real ground motion data of Kobe earthquake. The results of analysis are presented in the Figs. 14 & 15. Most of the models examined using the nonlinear time history technique showed irreversible permanent deformation. The models have been deformed permanently after reaching the maximum responses corresponding to input acceleration and fail to recover their initial or original state. Extracted from the nonlinear time history data are the changes in maximum responses for all models, which are displayed in Figs. 16 & 17. The results obtained from nonlinear time history analysis imply that with the increment of slope angle, displacement in the direction of force (*X* direction) increases for both regular & irregular buildings. In the transverse direction of force (*Z* direction), displacement increases with the increment of slope in regular structure, but reduces in irregular type of structures. However, in both cases the R-30 model inhibits very less or negligible result. Similar nature is noticeable in the case of maximum inter-storey drift at *X* and *Z* directions.

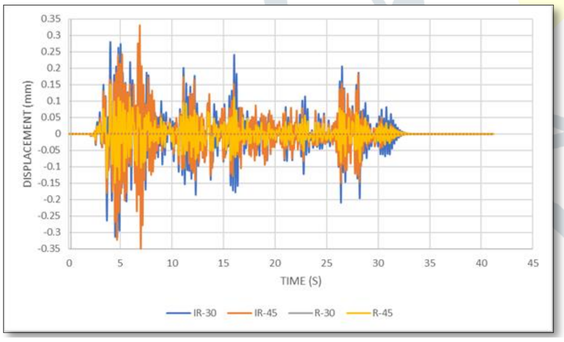


Figure 14 Displacement in X direction by NLTHM

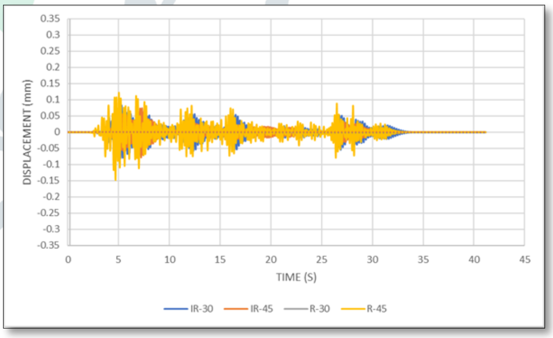


Figure 15 Displacement in Z direction by NLTHM

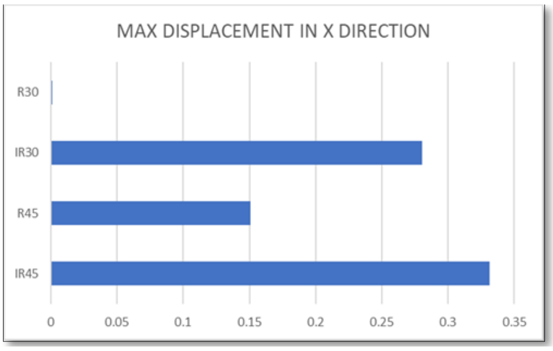


Figure 16 Maximum displacement in X direction in NLTHM

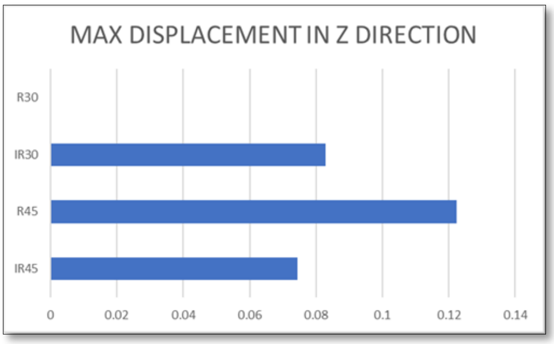


Figure 17 Maximum displacement in Z direction in NLTHM

IV. CONCLUSION

In this paper, seismic analysis has been performed in static and dynamic methods as well as in linear and nonlinear methods to evaluate the seismic behaviour of different kinds of fixed base building structure with specific configuration, resting on two-way sloping terrain with different slope angles like 30° & 45° respectively. It has been also discussed in the previous study that Structures on the sloping ground are found as more vulnerable than the structures on the plain ground, and as the slope angle grows, so does the degree of susceptibility. Under unidirectional force, natural time period increases and base shear carrying capacity reduces with increase of slope for all structures. These structures on sloping ground also reflect differential movement of either side of the structure, as the taller side moves more than the shorter side on upper portion of the building in the direction of force due to more column flexibility onto long column in lower side of the slope. This occurrence demonstrates the concentration of stiffness on the shorter side of the structure on the steeper slopes. So, the overall storey displacement is lesser in regular structures with decreasing in slope angle. however, the columns on the higher side of slope are also subjected to increased bending moment due to reduction of column height. The results of bending moment indicate the reduction with increment of slope angle in both kinds of building but regular building structure shows more effectiveness with increment of slope. Thus, the regular (R) kind of structures, resting on two-way slope, has exhibited less vulnerable & efficient results from the seismic performance point of view. Some improper estimation of forces and responses can affect the structures very badly. The negative impact of increasing slope angle on structures sitting on sloping ground is thus highlighted in this research, which also suggests taking extra care when designing both individual columns and entire structures.

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