Seismic Performance Study of Irregular 3D RC Frames from Pushover Analysis

Short and long column analysis on sloping ground

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Abstract:The major objective of the present study is to understand and quantify the influence of various parameters on the seismic behavior of RC structures. For this purpose 3D RC framed structures are modeled and analyzed using ETABS software. The analytical methodology adopted for the present study is non-linear static or pushover analysis. Pushover analysis is typically of displacement control type and is carried out as per the guidelines of ATC-40 and FEMA documents. In this report, procedure for seismic performance evaluation of reinforced concrete buildings is made. The capacity spectrum method (CSM) is used for estimating seismic inelastic displacement and evaluation of seismic performance of reinforced concrete buildings.

The present study focuses on the following three irregularities of RC framed structures,

- Short column effect due to structures on sloping ground
- Strong beam and weak column problem
- Vertical irregularities in the RC structures

The concept in earthquake engineering is to adopt strong column and weak beam mechanism so that the structures shows ductile behavior and doesn't undergo total collapse. However there may be instances of not adhering to this practice. Hence in the present study an attempt is made to understand the effect of strong beam weak column mechanism on the overall seismic behavior of structure. It is found that stiffness's of beams and columns significantly influence the base shear capacity and also the displacement ductility of the structure. The ductility of the structures can be increased by adopting the stronger columns compared to the strength as much as possible of beams. It is infusive that vulnerability of the structure can be reduced by increasing the stiffness of columns.

Influence of ground slope is to reduce the overall strength of the system. In case of structures resting on sloping ground, failure is likely to be because of expedience of base shear in the short columns rather than because of failure of overall structures. Also, structures resting on sloping ground are likely to be more vulnerable compared to those resting on plane ground. Influence of vertical irregularity is to reduce the seismic performance of the structures. In case of structures with more irregularity, the base shear carrying capacity and displacement ductility properties of the structures are reduced.

Keywords–Pushover Analysis, Capacity Spectrum, Vulnerability

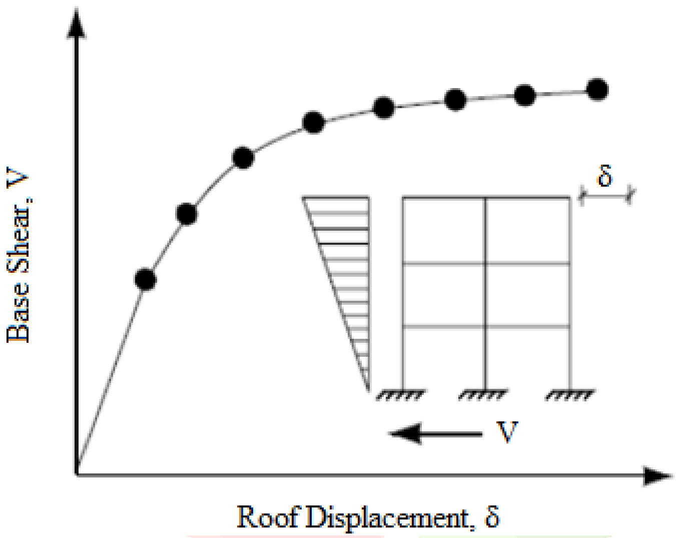
I. Introduction: The frequency, type and magnitude of earthquakes experienced over a period of time define the seismicity (seismic activity) of that area.Earthquakes can create serious damage to structures and are vulnerable to failure. The damage to structures causes deaths, injuries, economic loss, and loss of functions. Earthquake risk is associated with seismic hazard, vulnerability of buildings, exposed environment. Seismic hazard analyses quantify the probable ground motion that can occur atsite. Vulnerable buildingsmay cause risk to life and the seismic vulnerability of a structure can be described as its susceptibility to damage by ground shaking of a given intensity. The aim of a vulnerability assessment is to obtain the probability of a given level of damage to a given building type due to a typical earthquake. The level of damage is directly associated with deaths, injuries and economic losses. Damage functions are to be developed to assess the damage level for given magnitude of earthquake. Structural componentsare evaluated for serviceability in the elastic range of strength and deformation. Post-elastic behavior of structures could not be identified by an elastic analysis. However, post-elastic behavior should be considered as almost all structures are expected to deform in inelastic range during a strong earthquake.Although force-based procedures are well known by engineering profession and easy to apply, they have certain drawbacks compared to that of displacement-based procedures.

Elastic methods can predict elastic capacity of structure and indicate where the first yielding will occur, however they don't predict failure mechanisms and account for the redistribution of forces that will take place as the yielding progresses. Real deficiencies present in the structure could be missed. Moreover, force-based methods primarily provide life safety but they can't provide damage limitation and easy repair. The drawbacks of force-based procedures and the dependence of damage on deformation have led the researches to develop displacement-based procedures for seismic performance evaluation. Displacement-based procedures are mainly based on inelastic deformations rather than elastic forces and use nonlinear analysis procedures considering seismic demands and available capacities explicitly.

II. PUSHOVER ANALYSIS – NON-LINEAR STATIC APPROACH

In pushover analysis the structure is subjected to monotonically increasing lateral loads until target displacement is reached. A predefined load pattern is applied and increased till yielding in one member occurs then the structure is modified and lateral loads are increased further. **Sermin et al, (2005)** studied application of pushover of procedure for frame structures. He studied the effect of different lateral load patterns on capacity of structure. The pushover or capacity curve of the building is shown (Fig. 2.1). Lateral loads are increased till structure reaches its ultimate capacity. The pushover is expected to provide information on many response characteristics that cannot be obtained from an elastic static or dynamic analysis. The following are examples of such response characteristics are taken from **Krawinkler et al, (1998)**.

1. The realistic force demands on potentially brittle elements, such as axial force demands on columns, force demands on brace connections, moment demands on beam-to-column connections, shear force demands in deep reinforced concrete spandrel beams, shear force demands in un reinforced masonry wall piers, etc.
2. Estimates of the deformation demands for elements that have to deform in elastically in order to dissipate the energy imparted to the structure by ground motions.
3. Consequences of the strength deterioration of individual elements on the behaviour of the structural system.
4. Identification of the critical regions in which the deformation demands are expected to be high and that have to become the focus of thorough detailing.
5. Identification of the strength discontinuities in plan or elevation that will lead to changes in the dynamic characteristics in the inelastic range.
6. Estimates of the inter story drifts that account for strength or stiffness discontinuities and that may be used to control damage and to evaluate P-Δ effects.
7. Verification of the completeness and adequacy of load path, considering all the elements of the structural system, all the connections, the stiff nonstructural elements of significant strength, and the foundation system.



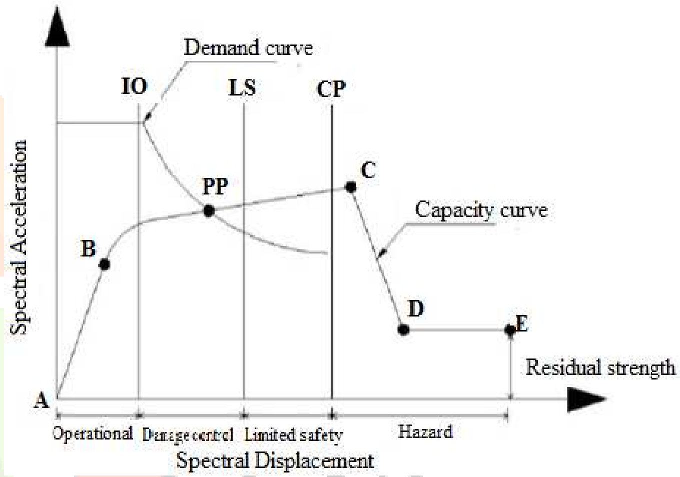


Fig.2.1: Pushover or capacity curve of the building (Sermin, 2005)Fig. 2.3: Capacity spectrum method (HAZUS MHMR 4)

IO- Immediate OccupancyLS - Life SafetyCP-collapse PreventionC- Collapse

(a). Implementation of Pushover Analysis

The process is to represent the structure in 3D analytical model that accounts for all important linear and nonlinear response characteristics, apply gravity loads followed by lateral loads in predetermined or adaptive patterns that represent approximately. The relative inertia forces generated at locations of substantial masses, and push the structure under these load patterns to target displacements that are associated with specific performance levels. The internal forces and deformations computed at these target displacements are used as estimates of the strength and deformation demands, which need to be compared to available capacities. The emphasis in performance evaluation needs to be on the following points.

1. Verification that an adequate load path exists.
2. Verification that the load path remains sound at the deformations associated with the target displacement level.
3. Verification that critical connections remain capable of transferring loads between the elements that form part of the load path.
4. Verification that individual elements that may fail in a brittle mode and are important parts of the load path are not overloaded.
5. Verification that localized failures (should they occur) do not pose a collapse or life safety hazard, i.e. that the loads tributary to the failed element can be transferred safely to other elements and that the failed element itself does not pose a falling hazard.

(b). Capacity Spectrum Method

ATC 40 (1996) has developed a simple iterative procedure to estimate seismic inelastic displacement for given level of earthquake. For seismic evaluation of existing structures the procedure can be easily implemented. This procedure requires pushover curve which is obtained from nonlinear static analysis of structure. Demand spectrum has to be developed for the given site considering level of earthquake (Serviceability earthquake (SE), Design earthquake (DE), and Maximum earthquake (ME)). This are defined based on percentage chances of probability of exceeding particular ground motion during 50 year time period. IS-1893 (2002) defines two levels of earthquakes (Design basis earthquake (DBE), Maximum considered earthquake (MCE)).

III. ANALYSIS OF SHORT AND LONG COLUMNS STRUCTURES

Accordingto our experience from pastearthquakes, disordered structures show higher potential fordestruction in comparison with other ones. Structuressuffer from such disorders mostly because of architecturalconsiderations, beauty, or technical necessities. Taking the generalslope into account, some of these considerations lead to the disorder in building height which appears as thedestructive phenomenon of short column at the lowest floor.

(a). BEHAVIOUR OF COLUMNS ON SLOPING GROUND

Many situations with short column effect arise in buildings. When a building is rested on sloped ground (Fig. 3.1), during earthquake shaking all columns move horizontally by the same amount along with the floor slab at a particular level (this is called rigid floor diaphragm action). If short and tall columns exist within the same storey level, then the short columns attract several times larger earthquake force and suffer more damage as compared to taller ones as shown in (Fig.3.2). The short column effect also occurs in columns that support mezzanine floors or loft slabs that are added in between two regular floors. There is another special situation in buildings when short-column effect occurs. Consider a wall (masonry or RC) of partial height built to fit a window over the remaining height. The adjacent columns behave as short columns due to presence of these walls. In many cases, other columns in the same story are of regular height, as there are no walls adjoining them. When the floor slab moves horizontally during an earthquake, the upper ends of these columns undergo the same displacement.However, the stiff walls restrict horizontal movement of the lower portion of a short column, and it deforms by the full amount over the short height adjacent to the window opening. On the other hand, regular columns deform over the full height. Since the effective height over which a short column can freely bend is small, it offers more resistance to horizontal motion and thereby attracts a larger force as compared to the regular column.

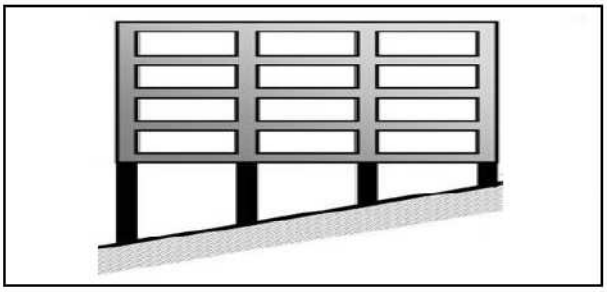


Fig.3.1 Ground floor on sloping ground (CVR Murty)

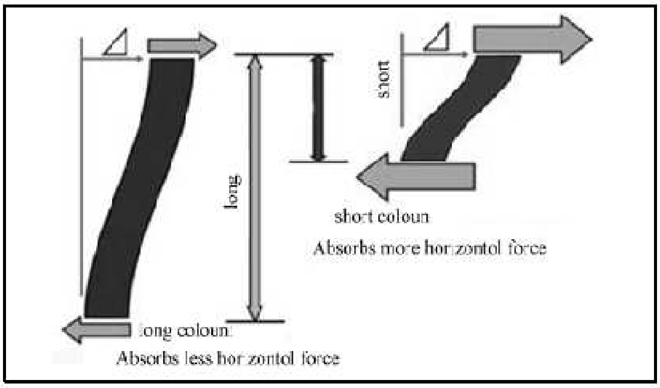


Fig. 3.2 Short and long column phenomenon (C.V.R.Murty, 2002)

(b). MODELING AND ANALYSIS

In the present work, 4-storey RC frames of varying ground slope alignment configurations are modeled by using 3D idealization and analyzed using ETABS pushover analysis capabilities. Default hinge properties are used for analysis and moment (M3) hinges are assigned for beams and coupled axial and moment hinges (PMM) are assigned for columns as per the recommendations of ATC 40(1996) and FEMA 356(2000).Pushover analysis is typically of displacement control type with loads applied as uniform acceleration in the lateral directions. The resulting base shears and roof top displacements are monitored to plot the pushover curve. In order to study the effect inclination of ground slope six different cases configurations have been defined from angle of slope (0 to 25). Considered earthquake zone is IV and lying on medium soil. Using M25 grade concrete and Fe415 steel.

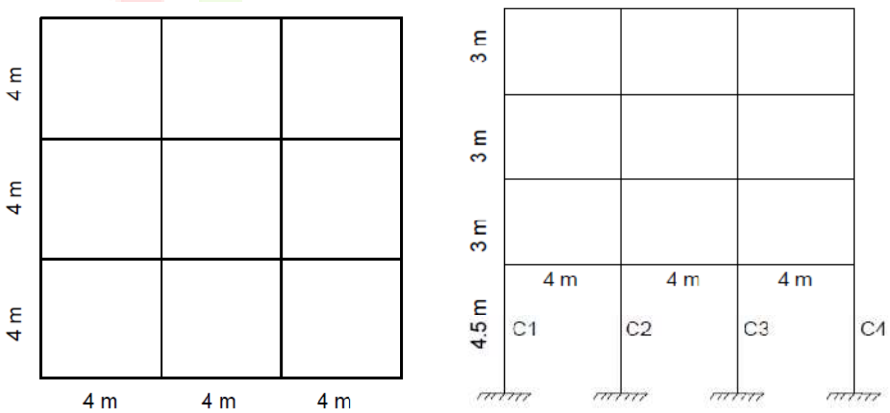


Fig. 3.3: Details of frame considered for the analysis

IV RESULTS AND DISCSSIONS

An attempt is made to study the effect of amount of inclination of ground slope, presence of setback buildings and both setbackstep back structures on the seismic performance of RC structure. The resulting capacity curve from the pushover analysis and thevulnerability assessment at various stages of pushover analysis are used to study the effect of these parameters on the seismicperformance of frames.Pushover analysis is carried out for 3D idealization for the above plan configurations. The resulting pushover curves for different number of storey are presented in (Fig. 4.1).

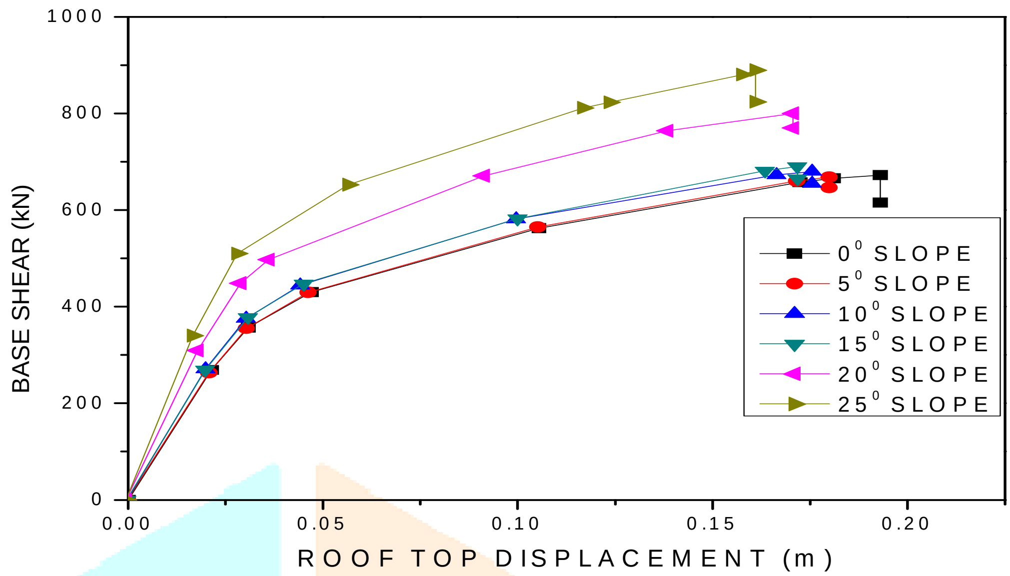


Fig. 4.1:Pushover curves for 4 storey frame with varying ground slopes

It is seen that ground slope have significant influence on the base shear carrying capacity of the structure. However, displacement characteristics of the frames significantly decrease as the slope of the ground increases. The Displacement and Base shear are calculated from the above Pushover Curves for zone IV, medium soil is represented in (Fig. 4.2).

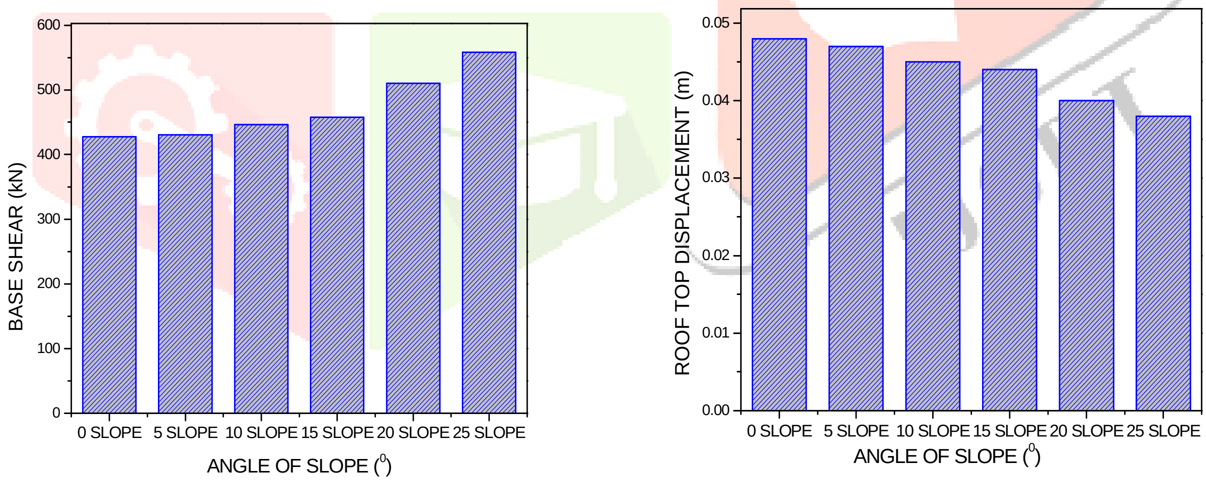
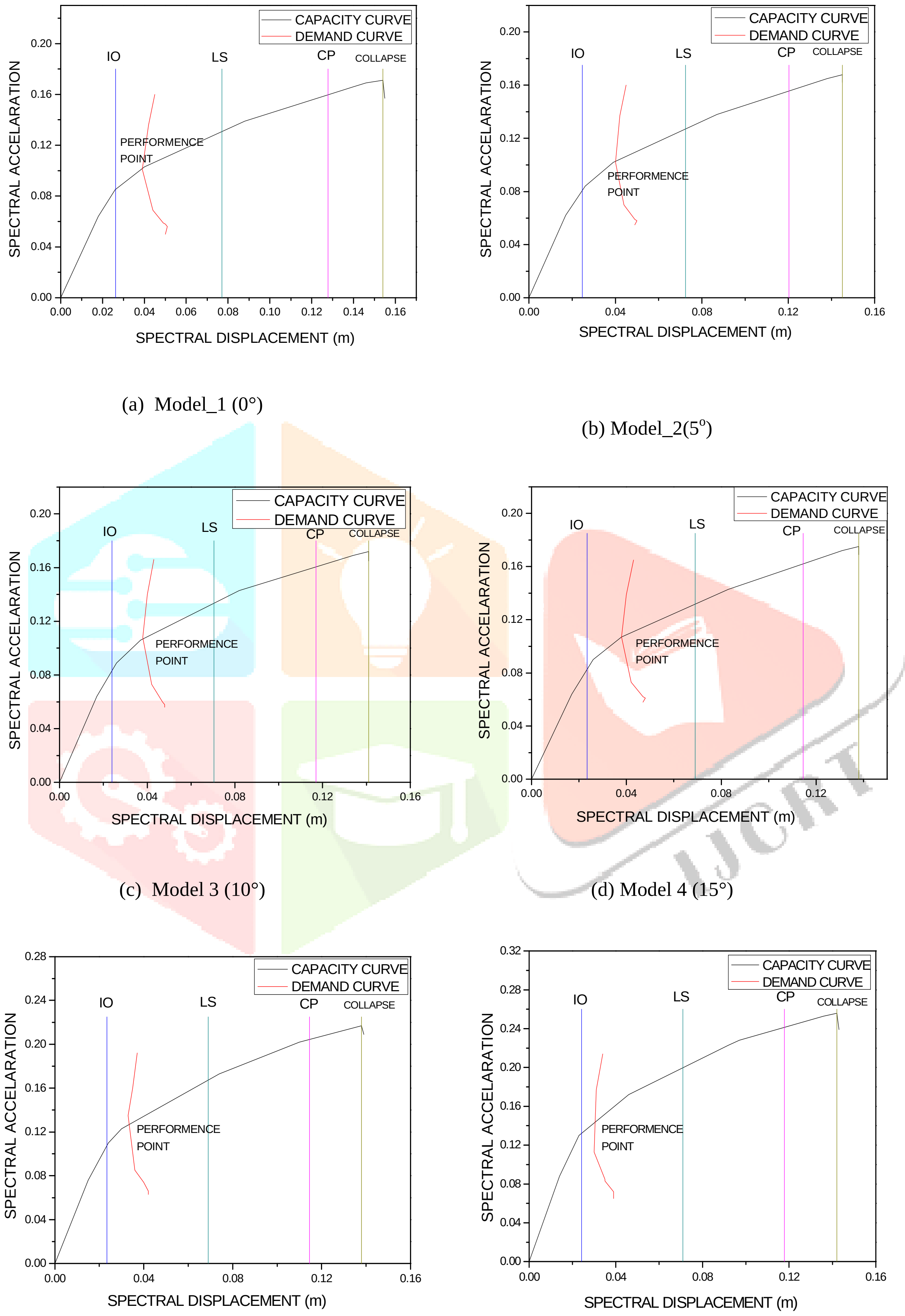


Fig. 4.2: Base shear and roof top displacement for structures with varying ground slopes

It can be seen that in all the cases shown above the base shear carrying capacity increases 10 to 12% for each 5 degree increase in ground slope. While the displacement of the structures decreases 8 to 10% for every 5 degree increase in ground slope. Hence, slope of ground has a greater effect on overall base shear and ductility of the structure. The location of performance point and identification of various damage states in acceleration-displacement response spectra (ADRS) format for 4-storey buildings for various angle of slopes is as shown in (Fig. 4.3).

Fig. 4.3(a) to Fig. 4.3(f) represents the capacity curves for the 4-storey frames for varying ground slope angles from 0° to 25°. The performance point for a design basis earthquake level of zone 4 and medium soil is also presented. It clearly represents the performance all the above structures are in the range of IO to LS but it shifted towards right (vulnerable) as the angle of slope increases. Further the shear force and bending moment diagrams in more vulnerable columns of the bottom storey are compared for various sloping ground structures in Table 4.1 and 4.2.



(a) Model_1 (0°)

(b) Model_2(5°)

(c) Model 3 (10°)

(d) Model 4 (15°)

(e) Model 5 (20°)

(f) Model 6 (25°)

Fig. 4.3: Performance point and different damage states for structures on varying ground slopes

Table 4.1:Comparison of shear force and bending moment in more vulnerable columns at various ground slope

Angle of slope	Location of most vulnerable column	Maximum Bending moment in vulnerable column (kN-m)	Maximum Shear force in vulnerable column (kN)	Status of Hinge in vulnerable column
0°	*Shortest column at bottom storey*	74.40	28.94	Elastic
5°		73.75	34.60	Elastic
10°		91.65	58.45	IO
15°		107.87	108.57	IO
20°		113.16	173.58	LS
25°		98.13	186.37	LS

Table 4.2:Comparison of shear force and bending moment in bottom storey columns at various ground slope

Value of Slope In Degree	Description of Column				
	C1	C2	C3	C4	BM & SF
0^o	65.56	72.14	72.14	65.56	kN-m
	24.37	28.78	28.78	24.37	kN
5^o	44.08	57.53	68.19	73.75	kN-m
	15.76	24.35	31.59	34.60	kN
10^o	26.77	43.19	64.20	91.65	kN-m
	8.64	19.10	35.30	58.45	kN
15^o	8.42	21.11	43.37	107.87	kN-m
	0.98	8.55	27.71	108.57	kN
20^o	6.28	10.70	19.65	113.16	kN-m
	0.27	2.56	8.78	173.58	kN
25^o	9.49	10.61	10.70	98.13	kN-m
	1.60	2.50	2.56	186.37	kN

In the present study, attempts are made to indicate the effectiveness of amount of ground slope in RC structures and formation of short columns and their seismic behavior are studied on four storey frames. Following are the inferences from the study.

- At 0^o slope, the bending moment and shear forces are symmetrically distributed over all the columns of the building.
- As the ground slope increases, shear force and bending moment keep shifting from longer column to shorter column.
- The ductility and roof top displacement of structures reduces with increase in ground slopes.
- Status of hinges in bottom storey columns changes from elastic (where ground slope is 0°) to collapse status (where ground slope is 25°).
- Most vulnerable column is shortest column located at upslope extreme point on the ground floor.
- Most vulnerable column attracts higher shear force and larger bending moments. However lateral displacements of all columns in ground floor remain nearly the same.

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