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BUILDING RESPONSE AND FRAGILITY CURVES FOR A HIGH-RISE BUILDING WITH AND WITHOUT SOFT STOREY WITH SOIL-STRUCTURE INTERACTION

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ABSTRACT

Ground floors of high-rise buildings are often kept open in order to facilitate the social and functional needs of the people such as parking spaces, open halls, etc. This creates a major weak point in this part of the building, causing the lateral forces to concentrate more on this point leading to the sudden change in response parameters along its height, making the buildings more vulnerable to collapse during seismic events. In this study, two residential buildings are studied: a high-rise building with a soft storey and a high-rise building without a soft storey to see their performances during earthquake events. The candidate buildings are located in Patna, India which is a major earthquake prone zone as per the seismic code of India. Non-linear time history analysis is performed for the two candidate buildings using SAP2000. Seismic response of these buildings are obtained in terms of structural acceleration, inter-storey drift etc. Incremental dynamic analysis has been performed to obtain fragility curves for various damage states of the buildings in order to show the comparative performances of the two buildings.

Keywords: *Building response, Fragility curves, High-rise building, Non-linear time history analysis, Soft-storey building*

1. INTRODUCTION

In the urban areas throughout the world multi-storied buildings have been constructed abundantly keeping the ground storey open. Such opening has been often kept for using the ground floor as parking and social gathering. Performances of such building have been very poor in past earthquakes. The soft or open ground storied buildings are vulnerable to damage during seismic events due to the fact that their ground stories have major weak points which cause the lateral force to concentration more than in any other parts of the buildings. This issue is due to the sudden change of stiffness along the height of these buildings, leading to sudden alteration of transmission of force in the building. The bare frame resists the loads through frame action only while in case of a soft ground storey frame; its upper stories resist the applied lateral loads both through frame action as well as through infill walls while its ground storey resists the loads only through frame action. This sudden alteration of transmission of force in the structure leads to the creation of soft storey mechanism in the building.

Indian state of Bihar has faced a number of moderate to severe earthquakes in the past and it lies in seismic zones IV and V with possible maximum intensity up to 8.4 on the Richter scale. Patna is the capital and most important city of Bihar. The city is located in seismic source zones which in reality are active faults. Patna has huge number of important public and private buildings with many of them are having soft or open ground stories. The main aim of this work is to obtain seismic response of a high-rise building and carry out incremental dynamic analysis to obtain IDA curve and fragility curve for the building with and without soft-storied in Patna. These curves can be used for emergency response and disaster planning, designing retrofitting schemes, risk mitigation, calibration of seismic codes etc. Soil-structure interaction (SSI) is considered in this study which may be the case for buildings situated on deep soft-soil deposits.

2. BUILDING MODELLING

Reinforced concrete ordinary moment resisting frame buildings are the most common type of building with varied number of storey, shape etc. in this region. These buildings are designed as per the conventional method of IS 456 (BIS, 2000) and ductile detailing is generally absent for these buildings in Patna. A representative nine-storied high-rise building is considered in this study the plan view of which is shown in Figure 1. M25 grade concrete is taken for all structural members while M35 grade concrete is taken for piles. HYSD415 grade steel is taken as all kind of reinforcement bar. slab of 150 mm thick is taken. Design is checked as per IS 456 (BIS, 2000) and IS 1893 (BIS, 2002). The building is designed as ordinary moment resisting framed residential building located at soil type II in Patna, which is in seisimic zone IV as per IS 1893 (BIS, 2002). Infill walls are modelled in the form of equivalent struts as “double braced multi-linear plastic link” elements followed by hysteretic Pivot model. According to Cavaleri and Di Trapani (2014) and Cavaleri and Di Trapani (2015), infill wall is mechanically characterized by the parameters the Elastic Young Modulus, Shear Modulus and Poisson Ratio. Plastic hinges are assigned to the numerical model for the sample building. Moment hinges (M3) as per Table 6-7 of FEMA 356 (Concrete Beams) (2000) are assigned at the ends of the beams. P-M2-M3 hinges as per Table 6-8 of FEMA 356 (Concrete Columns) are assigned at the ends of the columns to consider the interaction of axial force and bi-axial bending moments.

2.1 Modelling of Soil-structure Interaction

The soil is modelled as eight-nodded hexahedral solid brick element. The most prominent nature of soil in this region is soft soil. In this study, the boundaries which can fully absorb body waves propagating normal to the boundary proposed by Lysmer and Kuhlemeyer (1969) is used to model damping in the soil. The bottom surface of the soil is fixed. The depth and width of the absorbing boundary are taken as four (4B) and three (3B) times the width of the structure (B) from the centre of the structure in both sides. Pile soil interface is modelled using gap element (Cook et al., 2002). Side views of the building with soil-structure model and infill walls without and with soft storey are shown in Figure 1 and 2, respectively. The modelling is implemented using SAP2000 (CSI, 2013).

3. INPUT SEISMIC GROUND MOTIONS

3.1 Site Specific Design Spectrum

The time history data are required to be compatible with the target response spectrum representing the design seismic action at a site. Anbazhagan et al. (2015) developed the seismic hazard maps of Patna district considering the region specific maximum magnitude and Ground Motion Prediction Equations (GMPEs) by worst-case deterministic and classical probabilistic approaches. Normalized design spectrum at various zones for Patna for 5% damping from four zones for 2% and 10% probability of exceedance in 50 years is obtained from at rock site (Anbazhagan et al., 2015). In this study, the spectrum corresponding to the PSHA for 2% probability of exceedance in 50 years is selected as site specific design spectrum.

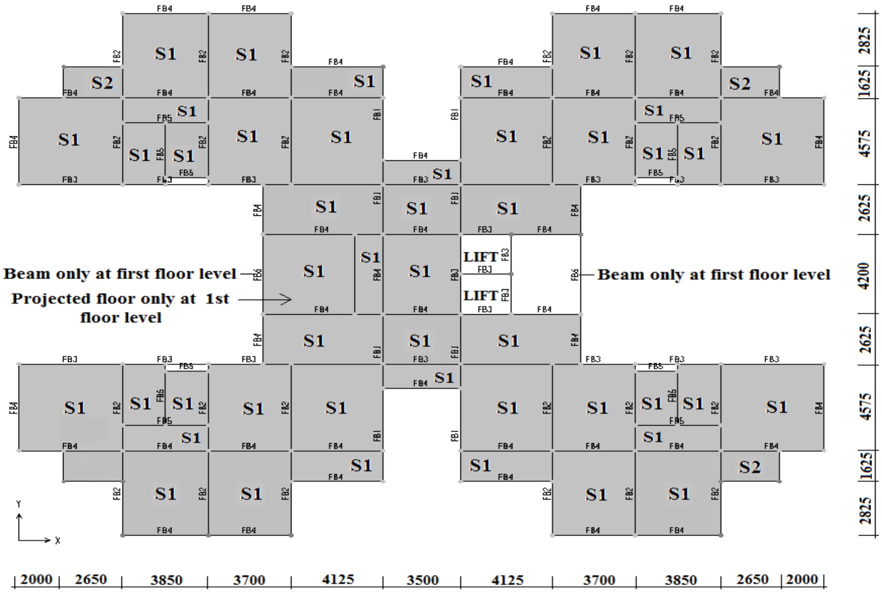

Figure 1: 1st floor plan of slab and floor beams of the building

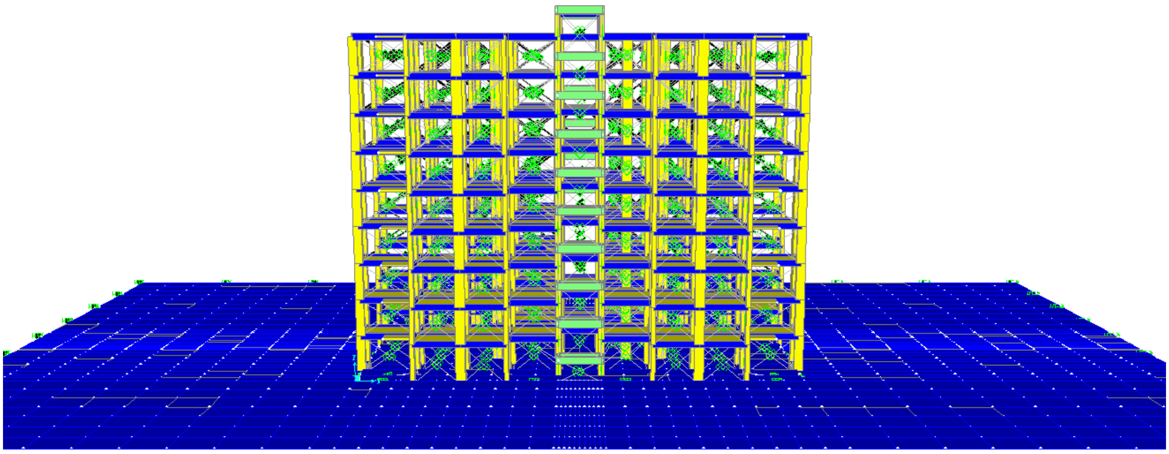

Figure 2: Side view of the building (without soft storey) with infill walls

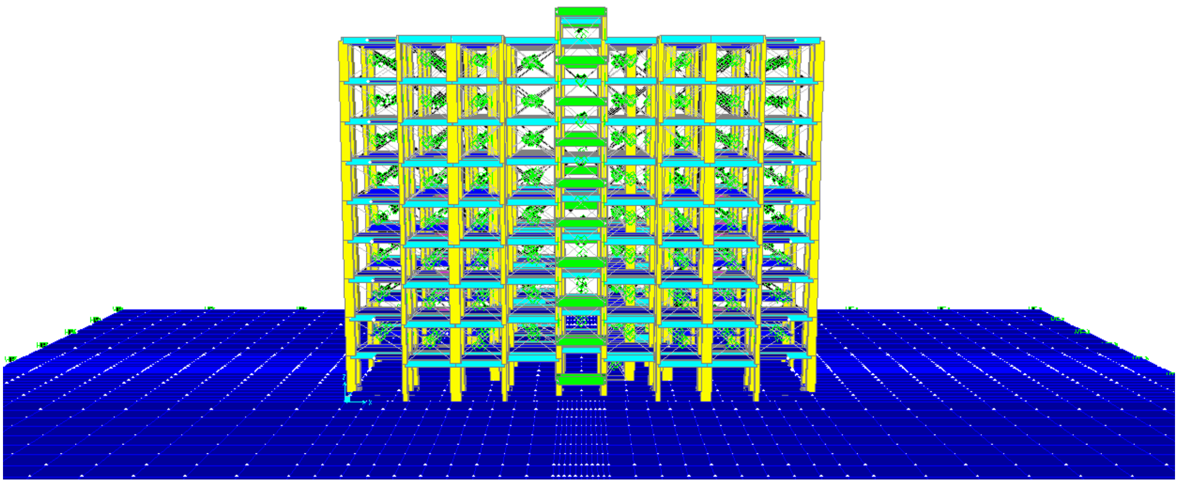

Figure 3: Side view of the building with ground floor as soft storey with infill walls

In this study, 30 pairs of raw ground motions as shown in Table 1 are selected from PEER Ground Motion Database (2015) based on the following parameters: Min and Max Magnitude (M_w) - 6 to 7.5; Min and Max Epicentral Distance (R_{rup}) : 10 to 500 km; Fault Mechanism Type : Reverse, Strike Slip; Min and Max Shear Wave Velocity (V_{S30}): 73 m/s to 385 m/s. The ground motions are selected also depending on the unscaled pseudo acceleration spectra falling in a particular range.

In this study, spectral matching is conducted using spectral matching program RSPMATCH developed by Abrahamson (1998) to all the 30 pairs of selected raw ground motions. Acceleration spectra of all scaled ground motions are compared with the target spectra of Patna as shown in Figure 4.

3.2 Soil Amplification

Shear wave velocity relations with SPT N value correlation equations for Patna are not available in literature. The correlations available in literature for IGB (Indo Gangetic Basin) as well as for regions for different soil conditions in the vicinity of Patna are studied. The equations used in this study are obtained from studies for Kolkata and Kanpur as the soil profile of these areas are similar to Patna. The amplification study is done using EERA (Bardet et al., 2000) for which the variation of shear wave velocity with depth is shown in Figure 5. The amplified ground motions are used as input for the buildings with SSI as some earlier studies have used the same ground motions for the analyses of the both models.

Table 1: Selected ground motions from PEER NGA database

RSN No.	Earthquake name	Year	Station Name	Magnitude	Mechanism	Vs30 (m/s)	Rrup (km)
12	Kern county	1952	"LA - Hollywood Stor FF"	7.36	Reverse	316.46	117.75
13	Kern county	1952	"Pasadena - CIT Athenaeum"	7.36	Reverse	315.13	125.59
15	Kern county	1952	"Taft Lincoln School"	7.36	Reverse	385.43	38.89
22	El Alamo	1956	"El Centro Array #9"	6.8	strike slip	213.44	121.7
36	Borrego Mtn	1968	"El Centro Array #9"	6.5	strike slip	213.44	222.42
37	Borrego Mtn	1968	"LA - Hollywood Stor FF"	6.63	strike slip	316.46	199.84
38	Borrego Mtn	1968	"LB - Terminal Island"	6.63	strike slip	217.92	207.14
39	Borrego Mtn	1968	"Pasadena - CIT Athenaeum"	6.63	strike slip	315.13	129.11
51	San Fernando	1971	"2516 Via Tejon PV"	6.61	Reverse	280.56	173.16
52	San Fernando	1971	"Anza Post Office"	6.61	Reverse	360.45	113.02
53	San Fernando	1971	"Bakersfield - Harvey Aud"	6.61	Reverse	241.41	214.32
54	San	1971	"Borrego	6.61	Reverse	338.54	112.52

	Fernando		Springs Fire Sta"				
1	Helena Montana	1935	"Carroll College"	6	strike slip	286.00	2.86
3	Humboly bay	1937	"Ferndale City Hall"	6.8	strike slip	219.31	71.57
6	Imperial Valley-02	1938	"El Centro Array #9"	6	strike slip	213.44	6.09
7	Northwest Calif-02	1941	"Ferndale City Hall"	6.6	strike slip	219.31	91.22
17	Southern Calif	1952	"San Luis Obispo"	6	strike slip	293.50	73.41
19	Central Calif-01	1954	"Hollister City Hall"	6.3	strike slip	198.77	25.81
24	Central Calif-02	1960	"Hollister City Hall"	6	strike slip	198.77	9.02
31	Parkfield	1966	"Cholame - Shandon Array #5"	6.19	strike slip	289.56	63.34
42	Lytle Creek	1970	"Cedar Springs Pumphouse"	6.53	Reverse Oblique	277.22	19.35
47	Lytle Creek	1971	"Lake Hughes #1"	6.53	Reverse Oblique	225.34	30.02
95	Managua Nicaragua	1972	"Managua ESSO"	6.95	strike slip	288.77	4.33
96	Point Mugu	1973	Hueneme "Gilroy Array #1"	6.59	strike slip	213.44	17.71
97	Hollister-03	1974	Gilroy "Hollister City Hall"	7.14	strike slip	128.14	10.46
98	Hollister-03	1974	Hollister "San Juan Bautista"	7.14	strike slip	198.77	9.39
99	Hollister-03	1974	"San Juan 24 Polk St"	7.2	strike slip	335.50	9.11
101	Northern California	1975	"Cape Mendocino"	7.36	Reverse	267.78	34.73
15	Kern county	1952	"Taft Lincoln School"	6.4	strike slip	385.00	38.89
10	Imperial Valley-03	1951	"El Centro Array #9"	6	strike slip	213.44	25.24

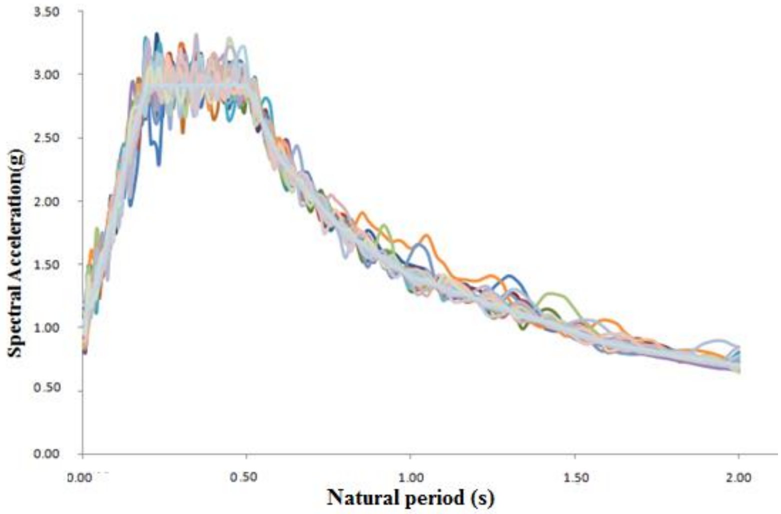

Figure 4: Comparison of spectra of 30 spectrally matched ground motions with the target spectrum

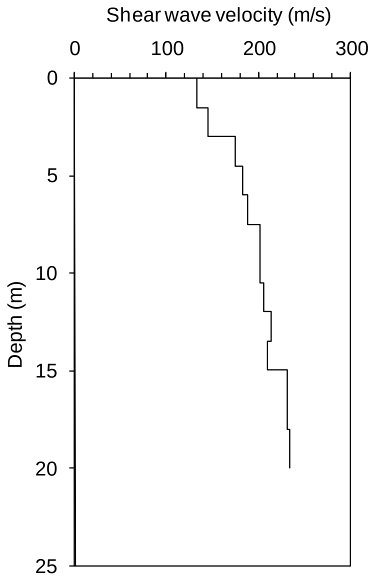

Figure 5: Borehole data used for present analysis

4. RESULTS OF NONLINEAR TIME HISTORY ANALYSIS

The results are shown in the form of median and dispersion of inter-storey drift, floor acceleration and average floor spectral accelerations between 0.0303s to 0.2s period (5-33 Hz) range for all stories through Figures 6-11. The responses are plotted with minimum, 16th percentile, median, 84th percentile, maximum values. The responses are plot shown for buildings without and with soft storey effect including SSI.

For the building with SSI fundamental period is found as 1.02 sec and for the same building with open ground storey (OGS) SSI structural system it is 1.38sec. This is due to decrease in stiffness of the system.

There is huge difference in dispersion pattern of the floor displacement for different storey when the model of building with and without OGS is compared. For the model without OGS floor displacement is increasing with the increasing storey level whereas for the model with OGS it is almost same with increasing storey level. The pattern of inter-storey drift ratio is also completely different for these two cases. For the model without OGS inter-storey drift ratio is increasing till 4th floor above which it is decreasing (Figure 6). In building model with OGS inter-storey drift ratio is maximum at the first floor and the value is decreasing with increasing floor levels (Figure 7). Maximum inter-storey drift ratio is at 4th floor for building without OGS and for the building with OGS it is at 1st floor.

The floor acceleration in case of building without OGS is higher (Figure 8) compared to the building with OGS (Figure 9). Trend of mean spectral acceleration values are similar in both cases except it is slightly higher for the building without OGS (Figures 9 and 10).

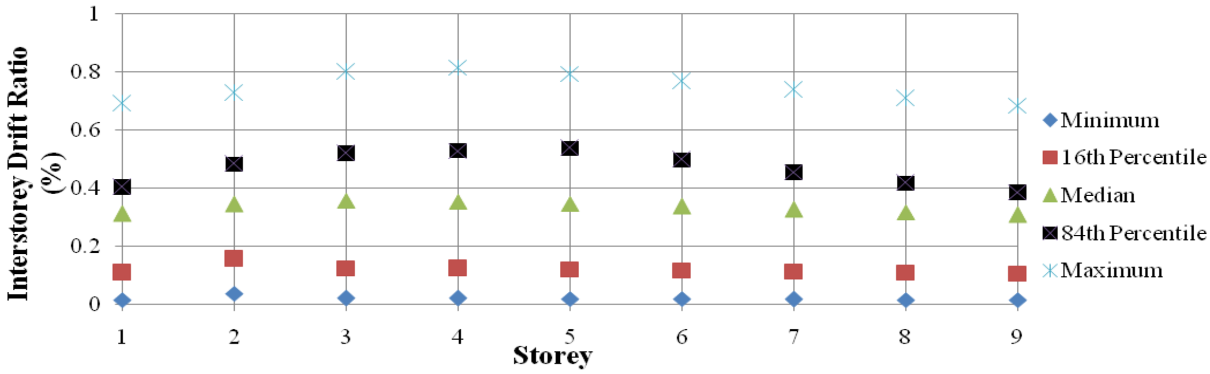

Figure 6: Inter-storey drift ratio for different floors for building without soft storey in x-axis

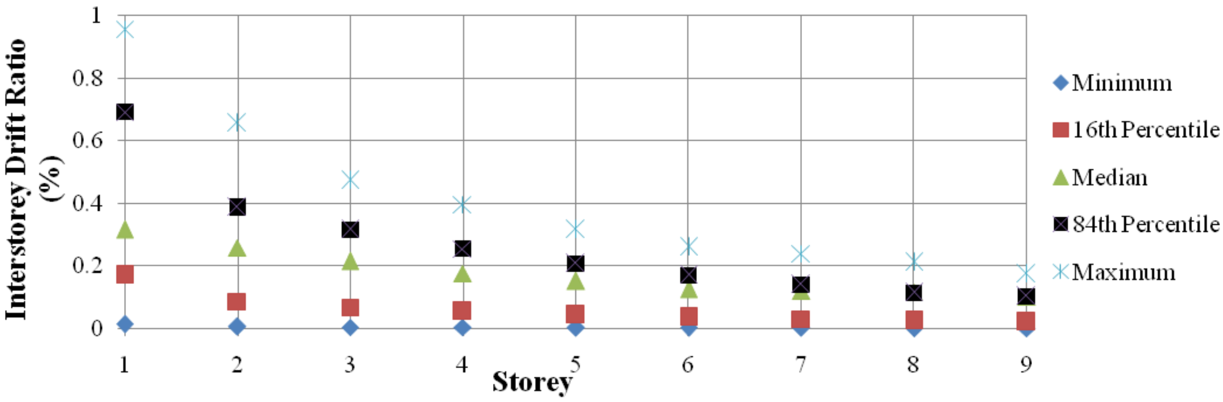

Figure 7: Inter-storey drift ratio for different floors for building with soft storey in x-axis

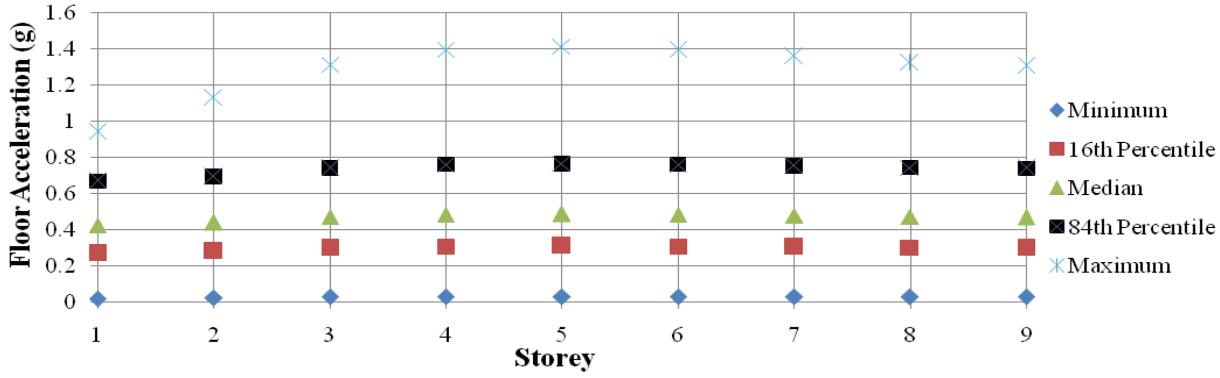

Figure 8: Floor acceleration for different floors for building without soft storey in x-axis

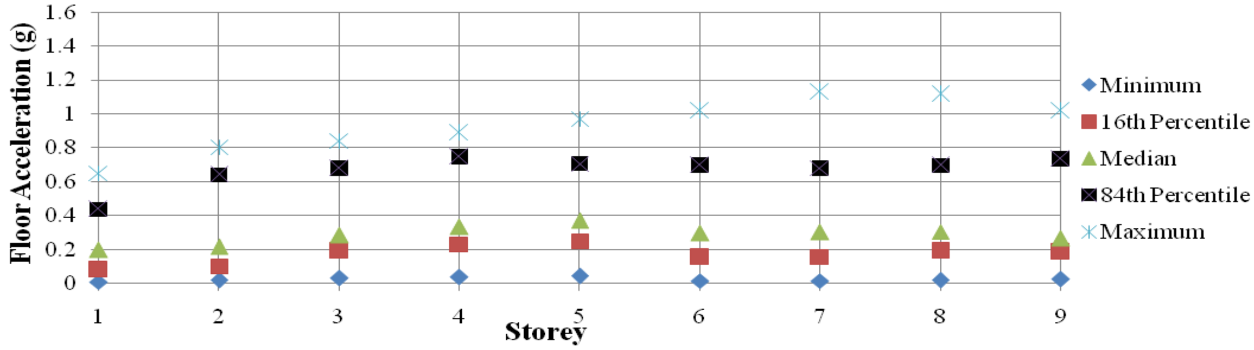

Figure 9: Floor acceleration for different floors for building with soft story in x-axis

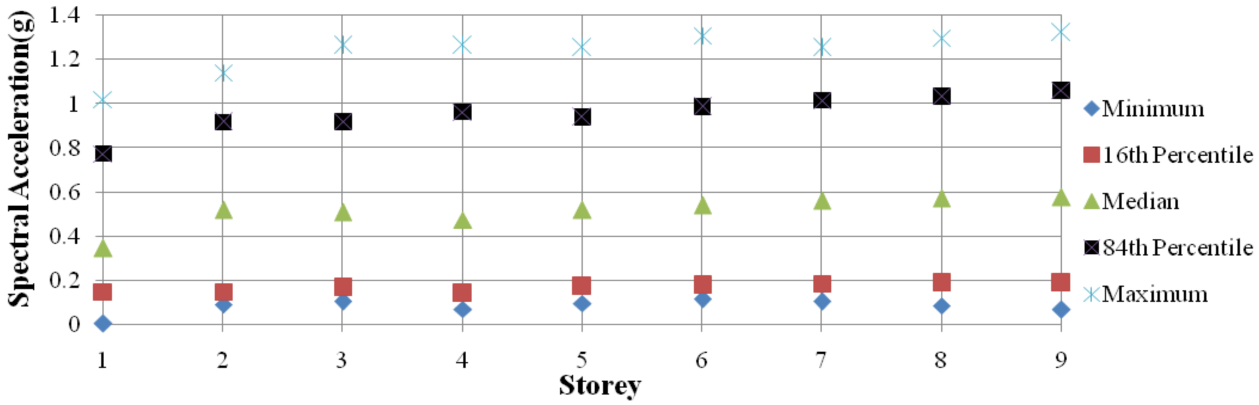

Figure 10: Average Floor Spectral Acceleration between 0.0303s to 0.2s for different floor for building without soft storey

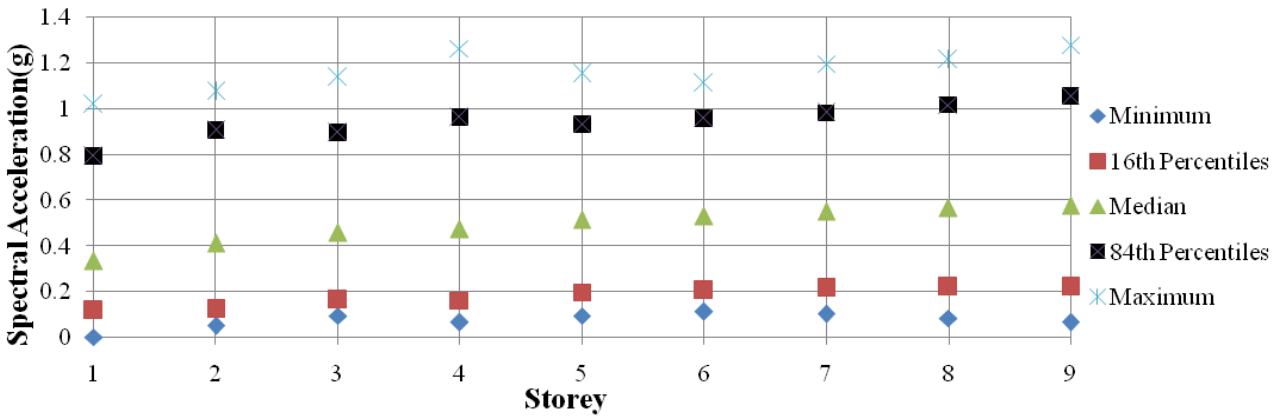

Figure 11: Average Floor Spectral Acceleration between 0.0303s to 0.2s for different floor for building with soft storey

5. DEVELOPMENT OF FRAGILITY CURVES

IDA curve is the plot of peak ground acceleration in ordinate and the inter storey drift ratio in abscissa. The curve is obtained by carrying out incremental dynamic analysis in which time history analysis is conducted a number of times for 30 pairs of acceleration time histories for various level of scaling. For each scaling level PGA as well as maximum inter-storey drift ratio is taken and the curve is plotted for each ground motion. IDA curve is the key requirement for plotting fragility curve by incremental dynamic analysis. Here a set of 30 ground motion is taken and 30 IDA curves are plotted in Figures 12 and 13. IDA curve is less scattered for low inter-story drift ratio values in case of building without OGS. The values are more scattered for low inter-story drift ratio for the building with OGS.

From the IDA curves of each ground motion, PGA values are calculated for IDR values corresponding to 0.63%, 1%, 2% and 4% which represent slight, moderate, extensive and complete damage states, respectively. Median and lognormal standard deviation values of PGA for each damage state are calculated and corresponding fragility curve for the same damage state is obtained by using cumulative normal distribution function. The comparison of fragility curves are shown in Figure 14 to Figure 15. Table 2 obtained from the fragility curves of buildings (Figures 14 and 15) clearly indicates that OGS in a building has increased the level of risk for all damage states. There is not much change in probability of exceedance in slight damage states. For moderate, extensive and complete damage states the risk increases with the application of OGS.

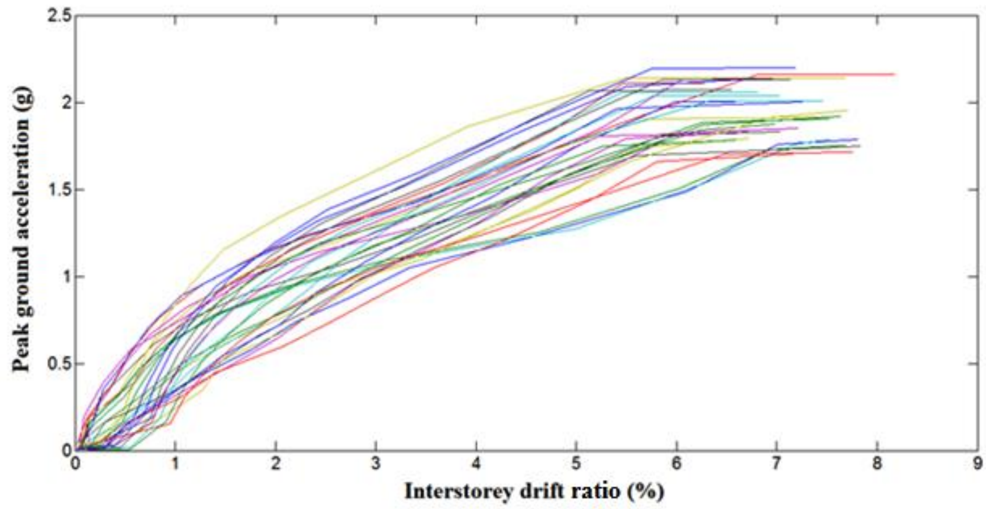

Figure 12: IDA curve of building without soft storey for 30 ground motions

Table 2: Result table

Max PGA	SHA	Damage state	Probability of exceedance	
			Building with SSI	Building with SSI & OGS
1.22g	PSHA, 2% probability of exceedance in 50 years	Slight	98%	100%
		Moderate	80%	97%
		Extensive	61%	78%
		Complete	37%	35%
0.456g	PSHA, 10% probability of exceedance in 50 yrs	Slight	48%	56%
		Moderate	19%	11%
		Extensive	10%	1%
		Complete	3%	0%

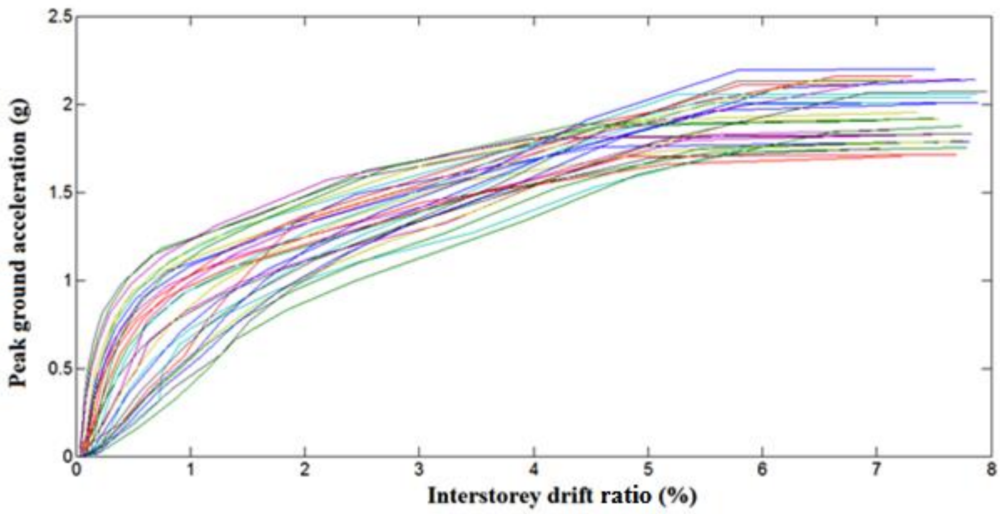

Figure 13: IDA curve of building with soft storey for 30 ground motions

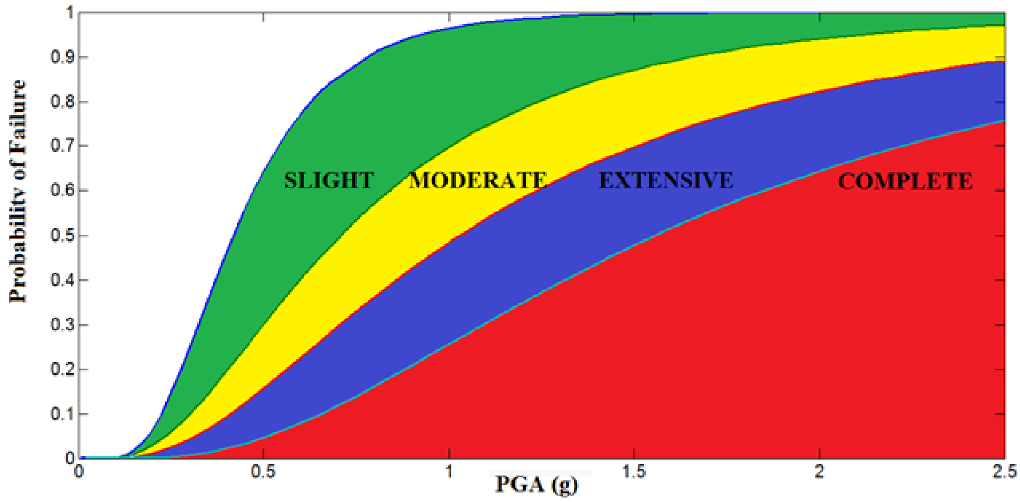

Figure 14: Fragility curve of building without soft storey

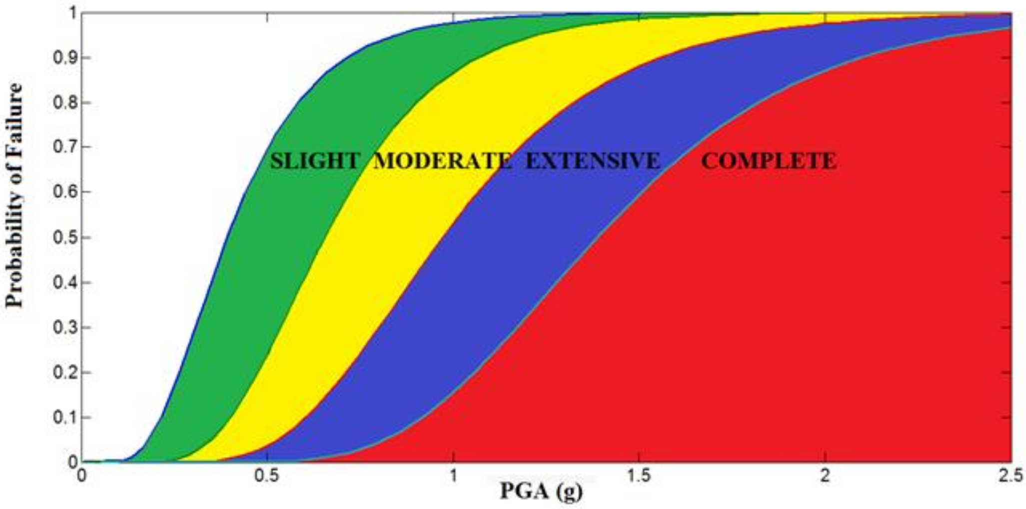

Figure 15: Fragility curve of building with soft storey

6. SUMMARY AND CONCLUSIONS

In this study a set of 30 raw acceleration time histories are used which are selected based on regional earthquake characteristics of Patna, to obtain spectrally matched and amplified ground motions and they are used to obtain fragility curves for a nine-storied building with and without open ground storey. For amplification of the ground motion, suitable shear wave velocity -'N' value correlations available in literature for different type of soil is selected. The knowledge of the buildings already present in Patna and the construction practices is also necessary to determine its importance and to model the building. The high-rise building is modeled in SAP2000 with SSI by gap/link element method, and dynamic non-linear analysis is carried out for obtaining the response of the building in terms of maximum inter-storey drift ratio, floor acceleration and mean spectral acceleration of all the floors. The study includes soil-structure interaction, which may be a case for buildings resting on soft-soil to derive the seismic fragility curves. It is shown through fragility curve that building with soft storey or open ground storey show increased probability of damage during earthquake.

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