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Seismic Fragility Assessment of RC Framed Structure under Varying Ground Motion Duration

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Abstract

Earthquakes are considered as the major unpredictable natural phenomenon often resulting in major disasters. Here in this study, the effect of the duration is isolated from other parameters related to ground motion like amplitude, and response spectral shape by assembling spectrally equivalent long and short duration pairs of records using Seismomatch and Seismosignal. The performance of buildings constructed in accordance with Nepal's National Building Codes of Practice in relation to seismic design is carried out. Incremental dynamic analysis is performed using SAP2000. From results, it shows that the lateral story displacements increase with the increase in duration. The collapse prevention state for 4-story buildings is attained at higher values of PGA compared to 7-story buildings with a decrement in value of PGA at collapse by 8.8% and 29% respectively for long-duration motions. The fragility curve shows the increase in the probability of collapse by 40% and 60% at 0.5g and 0.44g and there is an increase of 14% and 19% in collapse capacity ratio respectively for 4 and 7 -story building when significant duration value increased from 2 to 4 times. So, it is concluded that longer-duration earthquakes have significant effects on seismic responses of the structure.

Keywords

Long duration motion, Fragility Curve, Collapse Capacity, Incremental Dynamic Analysis

1. Introduction

Earthquakes are a major unavoidable and unpredictable natural phenomenon often resulting in major disasters including structures to living beings. Nepal being a seismic-prone country, witness earthquake at regular intervals of time. Kathmandu Valley and nearby areas are designated as a severe zone for an earthquake with a zone factor of 0.35 and soil type 'D' (which is a soft soil type) according to NBC 105:2019. The region has been widely damaged by various earthquakes like the 1408 Bagmati zone earthquake (Mw 8), 1767 Northern Bagmati zone earthquake (Mw 7.9), 1833 Kathmandu -Bihar earthquake (Mw 8),1988 Kathmandu Bihar earthquake (Mw 6.9). The latest earthquake, the Gorkha Earthquake 2015 with a moment magnitude of 7.8 caused a severe effect in various parts of the country including major destruction in the capital city Kathmandu along with a huge number of deaths. Prior to the Gorkha Earthquake, the seismic coefficient and response spectrum method was the only method used in structural engineering. The Nepal building code, however, makes use of additional trustworthy and widely accepted methods in its application. In any real earthquake, the time of shaking occurs in sequence with different duration, and their effects also seem to be different. The longer duration could result in accumulation that worsens the rigidity and strength of the structural components, destabilizing P-effects, and leading to more damage.[1][2].The seismic coefficient and response spectrum methodologies, as well as time history analysis, are all permitted by the Nepal building code. With an increasing number of high-rise buildings and also the occurrence of a large magnitude earthquakes worldwide, the need for vulnerability assessment has also increased. The amplitude, frequency content, and duration are widely recognized characteristics of the earthquake ground motions used for vulnerability assessment and are factors that affect the structural response. But the duration parameter is given second priority over the other parameters in general practice. In summary, Nepal lies in a seismically vulnerable zone and thus needs access to nonlinear behavior and fragility assessment of RC buildings for better prediction of the hazards including duration parameters along with other parameters.

2. Literature Review

Various studies conducted on analysis considering the variation in the duration of ground motion showed effects on collapse capacity displacement, base shear, and various other performance factors of the structure [3][4]. The response of the structure is affected differently depending on the ground motion's duration, and as duration increases, so does the pattern of damage accumulation. In a study of five-story steel frame buildings, the median collapse capacity for long-duration structures was found to be 29% lower than that of short-duration structures. [2]. Another study performed an experimental test on the reinforced column and discovered that the long-duration vibrations caused considerable damage compared to spectrally short-duration vibrations [5]. Similar to this, another study found that the period of the strong motion had a substantial impact on the structural response since it was considered to be a major factor in the increase in the number of earthquake cycles, which ultimately had an impact on the structure's strength.[6]. In a related study, 50 steel moment frames were examined using nonlinear dynamic analysis using spectrally equivalent pairs of short and long-duration earthquake records. It was found that the impacts of duration are important for structures that exhibit cyclic degradations. The reduction is about 20% on the collapse capacity and reaches up to 40% for those buildings with high cyclic degradation levels [7]. But only a few studies have been carried out considering duration as the parameter for analysis of seismic performance and they do show a significant effect on base shear, displacement, collapse capacity, and other factors. The existing codal provisions employed in the context of Nepal only take into account the duration of a single strong earthquake in the form of a response spectrum when performing time history analysis. But this is not enough to evaluate the seismic response of the structure. Constructing new structures or rehabilitation of the existing ones with better codes may prevent many hazards. So, it is a must to study the effect of duration along with their response spectrum, amplitude, and magnitude on the response of the structure on the nonlinear behavior of the structural components in order to be alert and prepared for the hazard it may bring.

3. Structural modeling

The study area for the research is Kathmandu Valley. Generally, the area comprises low to mid-story buildings though with the change of time construction of the high-rise buildings is increasing. So, Regular ordinary moments resisting RC framed structures of 4 and 7 stories are taken in the study. The study area falls under the severe seismic zone and has a seismic zone factor of 0.35 with a very soft soil profile according to NBC:105 (2020) [8]. Here in the study, no variations are made along the bay size or material property. The foundation and diaphragm are assumed to be rigid. The height of the building for each story is taken as 3.2 m and the bay length is fixed to 5 m each in both directions. The details of the sizes of the structural components mainly beams are columns are as stated in the table 1. The modeling and analysis for the study is carried out using the finite element modeling software SAP2000. Generation of the plastic hinges at the ends using default hinges is done to define nonlinearity in the beams and columns.

Table 1: Beam and columns sizes

S.N.	Number of story	Beam size(mm)	Column Size(mm)
1	4	250*350	350*350
2	7	250*450	450*450

The concrete of grade M20 with a unit weight of 23600 N/mm2 and Poisson's ratio of 0.2 and reinforcement properties of HYSD500 with a unit weight of 76900 N/mm2 and Poisson's ratio of 0.3 are taken. These values are presented in table 2. For simplicity, the infill walls are not modeled but their weight is only considered for the analysis. A total of 3.75 KN/m2 load is used as dead load inclusive of the floor finish and a live load of 3 KN/m2 is applied on the slab. The base conditions are assumed to be fixed.

Table 2: Material Properties

Material	Grade	Unit Weight (N/mm2)	Poisson's Ratio
Concrete	M20	23600	0.2
Reinforcement	HYSD500	76900	0.3

For defining the degradation that occurred to cycling loading Takeda hysteresis model is used. The model is as shown in figure 1 [9]. Based on the Takeda model, the Takeda hysteresis model employs a deteriorating hysteretic loop. This simple approach is more suitable for reinforced concrete than for metals and requires no additional parameters. Compared to the other model, less energy is lost[10].

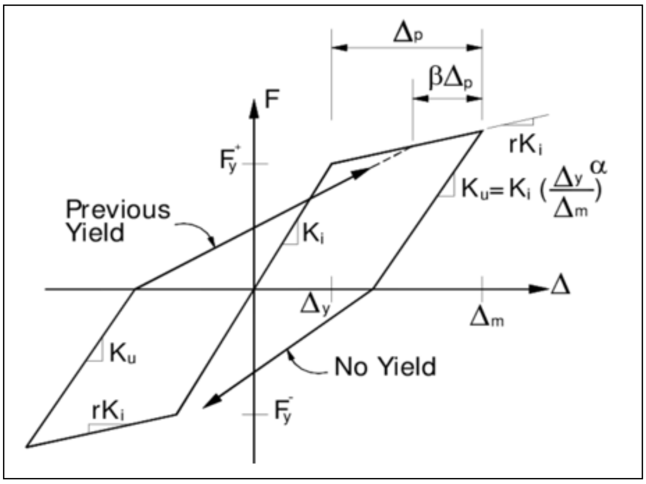

Figure 1: Takeda Hysteresis model

4. Ground motion details

It is very important to consider an appropriate number of ground motions for the interpretation of the proper results while conducting non-linear dynamic analysis. As stated in NBC 105:2020, the maximum values of the response quantities from these ground motions shall be used for ground motion records with fewer than seven numbers. However, if there are more than seven ground motions, the average values of the number of ground motions taken must be used to evaluate the response quantities.

So according to the above-stated statement, seven pairs of data are taken from the Pacific Earthquake Engineering Research (PEER) center's strong ground motion database and Consortium of the organization for Strong motion Observation System (COSMOS). The data taken are distinguished as long and short ground motions based on their significant duration value. It is the time needed to build Arias intensity (AI) in the equation's range of 5 to 75 percent of the total energy record. Long-duration ones are those having a significant duration longer than 25 seconds, whereas short-duration ones are those with a duration of less than 25 seconds. The pairs presented below are scaled to make them spectrally equivalent to the method presented by [2] and are then scaled to different scale factors to match the target spectrum of the considered study area i.e. Kathmandu valley using Seismomatch Software. Figure 2 displays a pair of spectrally identical long and short ground motion data with duration 2.

$$AI = \int_0^{tmax} a(t)^2 dt \tag{1}$$

Where,
AI=Arias Intensity
a(t)= acceleration time history
tmax=complete duration of recording a(t)

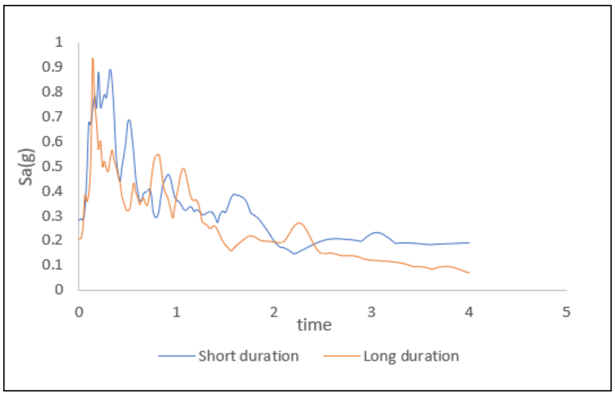

Figure 2: Response spectrum for spectrally equivalent pair of long and short duration ground motion.

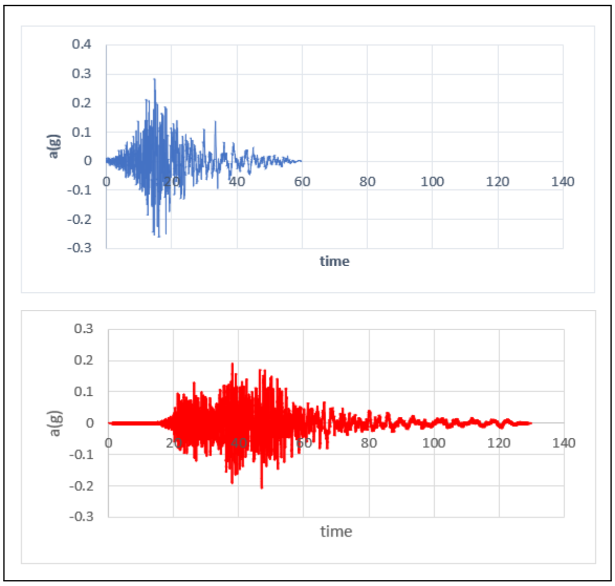

Figure 3: time series showing duration for spectrally equivalent pair of long and short duration ground motion.

In a similar way, the other 7 pairs of data are also made spectrally equivalent. The data used in the study are presented in table 3 Then these data are matched with the target spectrum of the area to make it usable for conducting non-linear dynamic analysis as shown in figure 3. The target spectrum is plotted as provided in NBC 105:2020 for defined seismic hazard conditions.

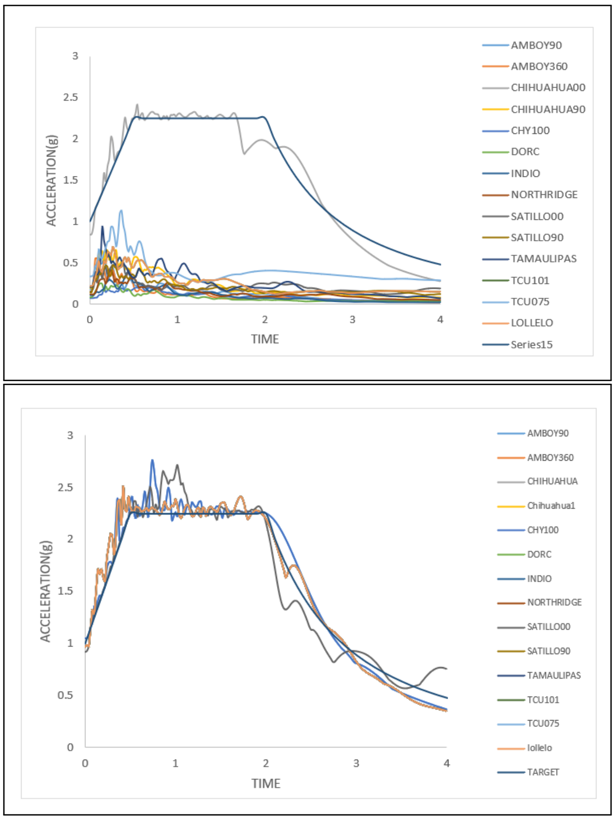

Figure 4: Unmatched and matched response spectrum of the ground motions.

5. Nonlinear Dynamic Analysis

Buildings don't react to strong ground shaking as a linearly elastic system. Therefore, nonlinear analysis is required for a more precise global displacement forecast and realistic seismic demand prediction. The P-effects and huge displacements that result from the structure's changing shape are the sources of the geometric non-linearity that gives rise to the nonlinear effects. The next is material non-linearity, which arises when concrete and steel are stretched beyond their proportionate limits and exhibit inelastic behavior, leading to cracking, crushing, yielding, and other issues.When applied forces and displacements exhibit a nonlinear relationship, the analysis is said to be nonlinear. It attempts to clearly represent the seismic performance of the structure and thus is considered an appropriate method for verifying the performance of the structure especially when responses are nonlinear. One of the effective techniques of the Performance-based Earthquake Engineering (PBEE) framework is incremental dynamic analysis. It involves a variety of scaled ground motion records being used in a number of nonlinear dynamic studies. The findings are helpful in evaluating the structural system's seismic performance[11].

In IDA, a proper structural model needs to be modeled on suitable finite element software like SAP, and ETABS. Secondly, the appropriate type and number of ground motion records need to be considered. These data need to be scaled to different intensity levels to carry out the dynamic analysis for extracting the results[12]. The results are presented in the form of the curves known as IDA curves . Peak Ground Acceleration (PGA) is taken as the Intensity Measure (IM) and the inter-story drift ratio (IDR) is chosen as the Engineering Demand Parameter (EDP) for the study. For Nonlinear design, a nonlinear gravity case is defined as the initial case including the total dead load plus 30 percent live load. The time integration method is used for which the Newmark-beta method is used. For geometric non-linearity, P-delta effects are accounted. Pdelta effect on columns are important cause it impose horizontal forces on main structure. Peak inter-story drift ratio (PIDR) are used to quantify the P-Delta impact.Displacement across the entire structure along every floor is analysed. Incremental Dynamic analysis is performed until inter-story drift ratio (IDR) is monitored as a 3% threshold. This value is designated as the collapse state of the structure, as recommended by[13].

6. Seismic behavior of the structures

6.1 Lateral Displacement

When structures are subjected to lateral loads like earthquake and wind loads, lateral displacement becomes important. Lateral displacement is dependent on the height and slenderness of the structure since taller buildings become more susceptible to lateral stresses because they are more flexible. The top-level experiences significantly greater lateral stresses than the bottom story, which causes the building to exhibit cantilever behavior. One of the characteristics of the investigation is lateral story displacements, as in [14]. The top story displacements for all the models are computed and the graph for displacements and significant duration is plotted as in figure 3 for all 7 pairs of the data.

Table 3: Ground motion data

SN	Earthquake	Station name	Scale	Duration	Source
1	2010 EL Mayor Cucapah	Chihuahua	-	27	PEER
2	2010 Drafield,New Zealand	DORC	2.97	16	PEER
3	2010 EL Mayor Cucapah	Ejido Satillo	-	33	PEER
4	1999 Chi Chi Taiwan	TCU075	0.54	18	PEER
5	2010 EL Mayor Cucapah	Ejido Satillo	-	33	PEER
6	1999 Chi Chi Taiwan	TCU101	0.82	16	PEER
7	2010 EI Mayor Cucapah	tamaulipas	-	27	PEER
8	1992 Landers	Amboy	1.55	17	PEER
9	2010 EI Mayor Cucapah	Chihuahua	-	25	PEER
10	1999 Hectormine	Amboy	1.47	11	PEER
11	1992 Landers	Indio- Coachella Canal	-	25	COSMOS
12	1999 Chi chi Taiwan	CHY100	1.62	12	COSMOS
13	1985 Valparaiso, Chile	Llolleo	-	28	COSMOS
14	1994 Northridge-01	Sun Valley - Roscoe Blvd	1.82	6	COSMOS

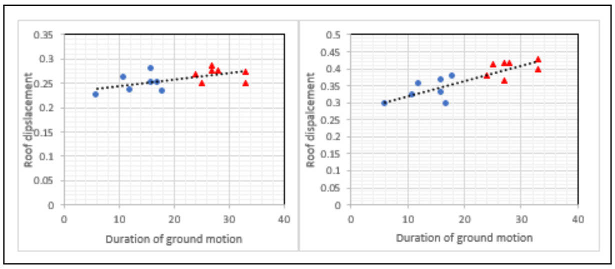

Figure 5: Displacement vs Duration graph for 4 and 7 story building

The regression line drawn after simulations of the 14 ground motion input (Seven pairs of spectrally matched short and long-duration ones) shows incremental order which indicates the increase in the value of the displacement with an increase in the time period of the ground motion. This demonstrates that a structure's vulnerability has risen. Also, the increment is higher for 7-story buildings compared to 4-story. Thus, the result advises that the duration of the ground motion should be considered while analyzing seismic performance.

6.2 Interstory Drift

In the study, inter-story drift is used as the engineering demand parameter and Peak ground acceleration as the intensity measure. The IDA curve is plotted through numerous simulations in SAP since it involves scaling of the input ground motion until collapse. The curve obtained through those simulations is later used for fragility analysis. The IDA curves plotted are presented in the figure 6, and 7 for both long and short-duration ground motions. The performance limits for the study are defined through performance-based seismic design as operational phase (OP), Immediate occupancy (IO), Damage control (DC), life safety (LS), and collapse prevention (CP) as per FEMA 356. The corresponding values for those performance limits are taken as in the study [13]. Here in this story the maximum limit or threshold is taken as 3% of IDR.

Table 4: performance limits

Limit state	Drift%
Operational Safety (OP)	0.5
Immediate Occupancy(IO)	1.0
Damage Control(DC))	1.5
Life Safety(LS)	2.0
Collapse Prevention (CP)	2.5

From the figure 6 and 7, it is clear that the higher story building attains a collapsed state at lower values of PGA as compared to lower story buildings. Also, on the occurrence of longer-duration earthquakes, the collapse state is attained at a lower value of the PGA for 4 and 7-story buildings.

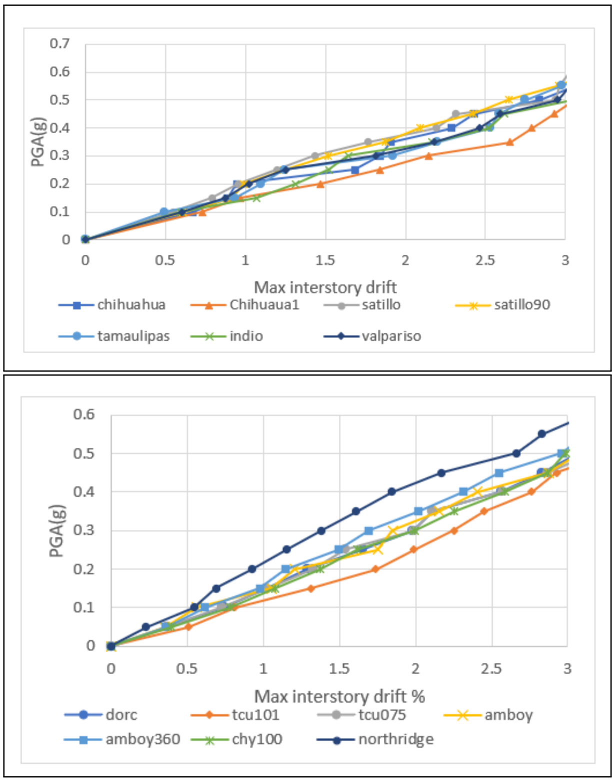

Figure 6: IDA curve under short duration ground motion for 4 and 7 story building

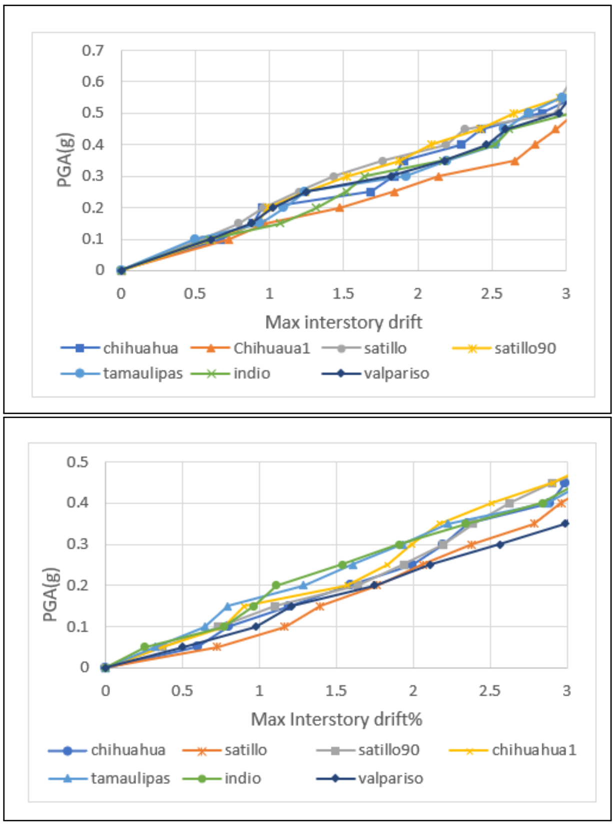

Figure 7: IDA curve under long duration ground motion for 4 and 7 story building

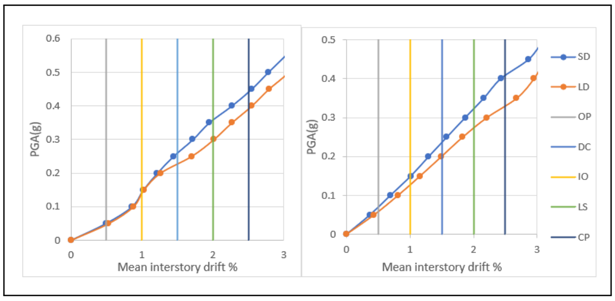

Figure 8: Mean IDA curve for 4 and 7- story building

For better interpretation, the above curves are plotted as mean IDA curves in figure 8. So from the mean IDA curve, it can be noted that the 4-story building reaches a CP state at 0.49g and 0.45g under short and long duration ground motion respectively which shows an increment of collapse capacity by 8.8%. While in the case of 7 story building, it attained a CP state at 0.4g and 0.31g respectively for short and long-duration motion with an increment in the value of PGA at collapse by 29%. This also concludes the remarkable increase in the vulnerability of the structure for longer duration ground motion and the importance of considering it in analysis and design.

6.3 Fragility Analysis

The fragility function is defined to be the function that, given a level of ground shaking, describes the chance of exceeding the various limit states. These are crucial resources for creating the fragility curve. The fragility curves are created in order to forecast future earthquake damage. During a seismic event, the fragility function can be directly employed to lower damage costs and fatalities. As a result, fragility curves can be utilized as a tool for decision-making in both pre-earthquake and post-earthquake scenarios. [15].

The following formulation is used in the study as presented in [11] for fragility analysis. Here, the Peak ground acceleration is used as the Intensity Measure while the maximum inter-story drift percentage is the damage measure. The particular formula used in the study is given below.

$$p(x) = \phi\left(\frac{\ln x - \mu}{\sigma}\right) \tag{2}$$

Where,
ϕ = standardize normal distribution
μ = mean of $\ln x$
σ = standard deviation of $\ln x$

Figure 9 and 10 shows the fragility curves. The structure attains its collapse point at a much lower PGA value under long-duration earthquake forces compared to short-duration earthquakes. This shows that when structures are subjected to long-duration earthquakes, the collapse capacity of the structure reduces significantly showing the insufficiency of considering only one earthquake without considering the duration parameters during design and analysis. Here OP1, IO1, DC1, LS1, and CP1 represent limit states for long duration motion and rest OP, IO, DC, LS CP for short duration motion.

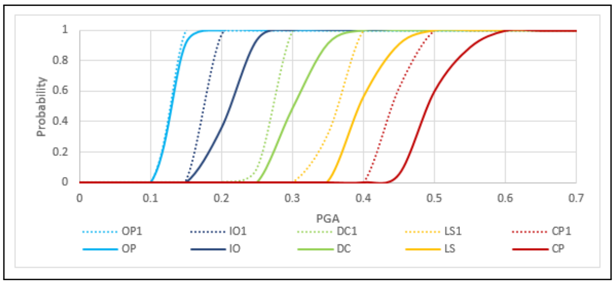

Figure 9: Fragility curves for 4 story building under long and short duration ground motion

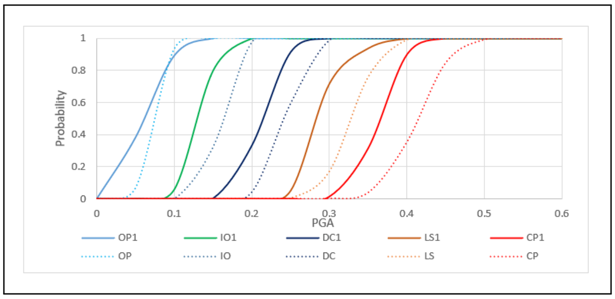

Figure 10: Fragility curves for 7 story building under long and short duration ground motion

As shown in figure 9, at 0.2g the OP and IO level for 4 story building has a probability of 100% under both long and short-duration earthquakes. At LS, DC, and CP levels, the probability is 0%. At 0.5g, the probability of exceeding and reaching the CP level is 100% for long-duration earthquakes while is only 60% for short-duration earthquakes. Similarly, from figure 10 , for the 7-story building OP level reaches 100% at 0.1g and CP at 0.2g. At 0.44g, the probability of CP level reaches 100% for long-duration earthquakes and 40% for short-duration earthquakes.

The increase in the probability of structure reaching the severe seismic state at lower values of PGA during the occurrence of a long-duration earthquake justifies that the occurrence of the long-duration earthquake reduces the strength of the structure to resist the damage considerably thus introducing the necessity of its consideration during seismic analysis.

6.4 Significant duration and collapse capacity

The relation between significant duration ratio and collapse capacity ratio for long and short-duration earthquakes gives a proper interpretation of the effect that the duration parameter shows in the collapse capacity of the structure.

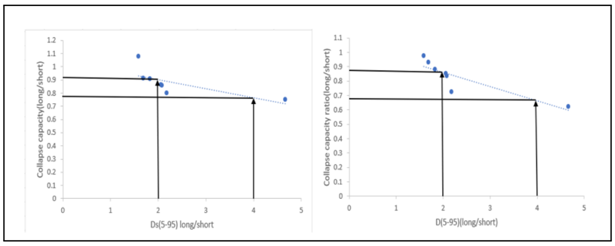

Figure 11: significant duration ration vs collpase capacity ratio for 4 and 7 story building under long and short duration ground motion

The value that has been highlighted above in figure11 left demonstrates that a ground motion with two times the duration of another predicts an average collapse capacity reduction of 8%, while a ground motion with four times the duration results in an average reduction of 22% for a four-story building. While for a seven-story building, a ground motion with twice the duration of another forecasts an average collapse capacity that is 15% lower, and one with four times the duration predicts an average collapse capacity that is 34% lower. This rise in % along with the considerable duration ratio clearly shows how duration affects collapse capacity. Additionally, the 7-story one has a higher % increase. This demonstrates how damage builds up as one rises in height.

7. Conclusions

The study is based on Kathmandu valley only. Incremental dynamic analysis is carried out for both long and short-duration ground motions for analyzing the seismic performance of the buildings 4 and 7-story. Results are interpreted in terms of roof displacement, interstorey drift, and probability of collapse taking intensity measure (IM) as Peak ground acceleration PGA. The following conclusions are drawn:

- The roof displacement value of the structure is increased when the structure got hit under long duration earthquake as compared to the short one. Also, the value of displacement increased with an increase in the height of the building. Thus, consideration of the duration in the analysis and design of the structure seems to be necessary.
- Mean IDA curves show the value of PGA attaining the collapse prevention state decreases by 8.8% and 29% respectively for 4 and7 story buildings under long duration motion compared to short duration ones. For safety, the higher values of PGA are safer as per our study. So, this also shows the effect of longer-duration motions.
- Fragility curve shows the collapse at 0.5g and 0.44g for 4 and 7-story buildings respectively showing the decrease in value of PGA at collapse by 14%. Also, the increment in the probability of collapse by 40% and 60% respectively for long-duration motion shows the increase in vulnerability of structure under its effect.
- There is an increase of 14% and 19% in collapse capacity ratio respectively for 4 and 7-story buildings when the significant duration ratio value increased by 2 times to 4 times. The increment in the collapse capacity ratio with an increase in significant duration ratio value also shows the possibility of the structure collapsing sooner under longer duration motion. Thus, showing the influence of ground motion duration on the seismic performance of the structure.

Therefore, when designing and analyzing the structure, it is essential to take the impacts of ground motion duration into account in order to make the structure seismically resilient.

Acknowledgments

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