CHAPTER 4

NONLINEAR AMPLIFICATION MODEL IN RC FRAME STRUCTURES: AN EXAMPLE OF CHI-CHI EARTHQUAKE

In this chapter, non-linear acceleration amplification models are proposed, which not only depends on the normalized height of the structure but also on the range of ground acceleration and the natural period of the structures. For this, five moments resisting RC frame models of 2,4,6,8 and 10 storeys are considered. A large number of ground motion data, having the range of less than 0.067g, twenty-nine ground motion data in the range of 0.067g to 0.2g and twenty-four ground motion data in the range of 0.2g to 0.3g respectively are accounted. Linear time history method is used for the analysis of all models. Based on the results, the non-linear amplification model is proposed and compared with the previously reported models.

4.1 EXISTING MODELS

The ASCE and Fathali models has been taken for the compaction of the obtain acceleration amplification values. The ASCE model performed the linear behaviour as the height of the building increases, however, the Fathali model showed non linear behaviour as the height of the building increases. For obtaining the acceleration amplification factor Fathali model gave two constant parameter based on the seismic ranges. The ASCE and Fathali modes was describe in chapter 2.

4.2 PROPOSED MATHEMATICAL MODEL

ASCE formula is based on the normalized height of the structure only and does not depend upon the natural period of the structure. However, Fathali's model observed the acceleration amplification factor depends not only on the normalized height of the structure but also on seismic ground motion range. It was also marked that, the acceleration amplification factor was depend on the period of the structure. However, it notifies that the shape of the amplification factor is nonlinear in the present case whereas the previous model showed a linear behaviour which gave conservative results. Based on these factors a mathematical model is proposed as shown:

$$\Omega = 1 + \left(\frac{Tmax-T}{T*a}\right) \mathrm{y}(y^5)^{y^4}, \tag{4.1}$$

where T_{max} is the maximum structural period, and the recommended value is 2.5 second [86]. T is the period of supporting structure for which the peak roof acceleration is not less than PGA. "y" is represented as the normalized height (z/h) of the structure, and "a" represent constant which depends upon the period of supporting structure and the seismic ground motion range. Values of "a" given in Table 4.1.

Table 4.1 Values of "a" based on ground motion range and period of supporting structure

Ground Motion Acceleration	"a"	Period of Supporting Structure
PGA=0.04S_{DS} <0.067g	2.25	0<T<0.5sec
	1.1	0.5sec≤T<1.0sec
	0.8	1.0sec≤T<1.5sec
0.067g≤PGA=0.04S_{DS} <0.2g	2.25	0<T<0.5sec
	1.25	0.5sec≤T<1.0sec
	0.85	1.0sec≤T<1.5sec

$0.2g \leq PGA = 0.04S_{DS} < 0.31g$	2.25	$0 < T < 0.5sec$
	1.25	$0.5sec \leq T < 1.0sec$
	0.75	$1.0sec \leq T < 1.5sec$

The non-linear general exponential function is obtained with the help of Euraqa Pro [142] software which is an artificial intelligence-based power modelling engine. Euraqa pro software is mainly used to determine the mathematical equations that describe sets of data in their simplest form. For the proposed mathematical equation, first step is to determine the natural period of the structures. Next step is to obtain the non-linear equations using Euraqa pro software. Finally, is to determine the constant "a" based on intensity of ground motion and period of the supporting structures using with trials and error method and to obtain the satisfactory values given in table 4.1, respectively.

4.3 BUILDING CONFIGURATION

In this paper, five RC moment-resisting frame structures of two, four, six, eight, and ten stories are considered. The supports of the models are fixed. The first storey height is 4m, and subsequent storey height is 3.4m. The 2D models are shown in Figure 1 and the size of the beams and columns are given in Table 4 in chapter 3. The fundamental period of the structures lies in the ranges of 0.1 to 1.5 second and the damping ratio is 5%. For the analysis of all the models, Etabs [141] software has been used.

4.4 GROUND MOTION SELECTION

Many researches worked with the higher range of the ground acceleration (higher than 0.3g), but most of the cases, the buildings are damaged at a low degree of the ground motion. Therefore, in this chapter to study the behaviour of the structures with a lower range of ground acceleration (0.01g to 0.32g). The selection of the ground motion was obtained from the strong ground motion virtual data centre [140]. For the analysis of the models, time history data having ranges between 0.01g to 0.31g is taken, and it divided (0.01g to 0.067g, 0.067g to 0.2g and more than 0.2g) based on Fathali [139]. In this study, 28 recorded ground motion data are between 0.01g to 0.067g, 29 ground motion data in the range of 0.067g to 0.2g and 24 ground motion data are between 0.2g to 0.31g. Details of the ground motion data are given in Table 4.2,4.3 and 4.4 as below.

Table 4.2 Recorded ground motion data having ranges 0.01g to 0.067g

Ground motion name	**PGA (g)**	**T (sec)**	**T_P (sec)**
Chi-chi 1 (TCU138)	0.066	64.992	16.696
Chi-chi 2 (TCU075)	0.057	52.98	17.005
Chi-chi 3 (TCU049)	0.044	47.975	15.66
Chi-chi 4 (TCU067)	0.047	47.975	16.115
Chi-chi 5 (HWA020)	0.0199	45.988	17.14
Chi-chi 6 (HWA035)	0.027	45.988	16.112
Chi-chi 7 (TCU052)	0.028	63.98	22.875
Chi-chi 8 (TCU048)	0.0237	63.98	26.69
Chi-chi 9 (TCU053)	0.0372	53.98	20.615
Chi-chi 10 (TCU109)	0.066	70.97	15.56

Chi-chi 11 (CHY102)	0.0516	70.97	16.23
Chi-chi 12 (TCU074)	0.0441	50.98	18.42
Chi-chi 13 (TCU052)	0.0352	50.98	17.14
Chi-chi 14 (TCU107)	0.0592	60.98	18.1
Chi-chi 15 (TCU082)	0.0503	60.98	13.73
Chi-chi 16 (TCU109)	0.0467	56.985	14.305
Chi-chi 17 (TCU089)	0.0492	56.985	16.775
Chi-chi 18 (TCU048)	0.0361	62.98	25.205
Chi-chi 19 (TCU076)	0.065	62.98	17.275
Chi-chi 20 (TCU084)	0.0662	74.98	14.69
Chi-chi 21 (CHY029)	0.066	62.98	17.275
Chi-chi 22 (CHY067)	0.0604	59.98	15.656
Chi-chi 23 (TCU120)	0.0574	59.98	18.694
Chi-chi 24 (TCU052)	0.0511	62.988	19.476
Chi-chi 25 (HWA035)	0.0514	62.988	20.66
Chi-chi 26 (TCU057)	0.024	49.992	16.004
Chi-chi 27 (TCU100)	0.0185	49.992	15.872
Chi-chi 28 (TCU082)	0.0439	56.992	20.424

Table 4.3 Recorded ground motion data having ranges 0.067g to 0.2g

Ground motion name	**PGA (g)**	**T (sec)**	**T_p (sec)**
Chi-chi 1 (TCU067)	0.1374	60.98	17.74
Chi-chi 2 (CHY024)	0.1348	60.98	15.93
Chi-chi 3 (CHY028)	0.1217	56.985	13.905
Chi-chi 4 (CHY035)	0.1179	56.985	15.08
Chi-chi 5 (HWA035)	0.1092	57.975	15.99
Chi-chi 6 (TCU071)	0.147	65.045	14.58
Chi-chi 7 (TCU122)	0.1215	65.045	14.475
Chi-chi 8 (CHY028)	0.1167	70.97	16.555
Chi-chi 9 (HWA032)	0.127	70.97	17.265
Chi-chi 10 (TCU070)	0.1913	65.045	16.81
Chi-chi 11 (TCU109)	0.1565	65.045	16.545
Chi-chi 12 (CHY024)	0.1654	65.045	15.6
Chi-chi 13 (CHY028)	0.1692	65.045	16.0
Chi-chi 14 (CHY029)	0.1439	63.985	14.275
Chi-chi 15 (CHY035)	0.1624	65.045	14.45
Chi-chi 16 (CHY041)	0.1517	65.045	14.73

Chi-chi 17 (CHY046)	0.1322	66.005	13.45
Chi-chi 18 (CHY074)	0.1234	66.005	16.125
Chi-chi 19 (CHY087)	0.1866	74.98	17.235
Chi-chi 20 (TCU076)	0.155	74.98	15.04
Chi-chi 21 (TCU122)	0.157	61.98	16.72
Chi-chi 22 (TCU129)	0.197	74.985	15.47
Chi-chi 23 (TCU109)	0.1344	96.985	11.85
Chi-chi 24 (TCU049)	0.1863	96.07	16.635
Chi-chi 25 (TCU075)	0.1563	93.985	12.685
Chi-chi 26 (TCU071)	0.1883	96.985	12.02
Chi-chi 27 (TCU078)	0.1831	99.03	10.715
Chi-chi 28 (CHY024)	0.1699	61.99	9.66
Chi-chi 29 (TCU116)	0.1829	71.0	14.38

Table 4.4 Recorded ground motion data having ranges 0.2g to 0.32g

Ground motion name	**PGA (g)**	**T (sec)**	**T_p (sec)**
Chi-chi 1 (TCU074)	0.2296	47.99	8.015
Chi-chi 2 (TCU067)	0.2167	74.985	11.94

Chi-chi 3 (CHY080)	02061	86.485	17.615
Chi-chi 4 (TCU075)	0.2252	124.06	10.04
Chi-chi 5 (TCU078)	0.2779	65.005	5.8
Chi-chi 6 (CHY024)	0.2347	68.03	15.22
Chi-chi 7 (TCU129)	0.2678	68.03	15.39
Chi-chi 8 (TCU138)	0.2818	74.98	12.15
Chi-chi 9 (CHY029)	0.2164	77.49	19.62
Chi-chi 10 (CHY034)	0.2465	63.985	1428
Chi-chi 11 (CHY035)	0.2504	139.98	36.02
Chi-chi 12 (CHY041)	0.2021	122.97	37.19
Chi-chi 13 (CHY074)	0.2449	149.97	37.53
Chi-chi 14 (CHY086)	0.2206	143.97	31.98
Chi-chi 15 (TCU034)	0.201	139.98	20.14
Chi-chi 16 (TCU049)	0.2515	149.97	46.14
Chi-chi 17 (TCU089)	0.2828	149.97	33.97
Chi-chi 18 (TCU102)	0.2820	149.97	34.05
Chi-chi 19 (TCU120)	0.2656	60.03	10.965
Chi-chi 20 (TCU122)	0.2598	149.97	47.37
Chi-chi 21 (TCU138)	0.2229	149.97	29.39

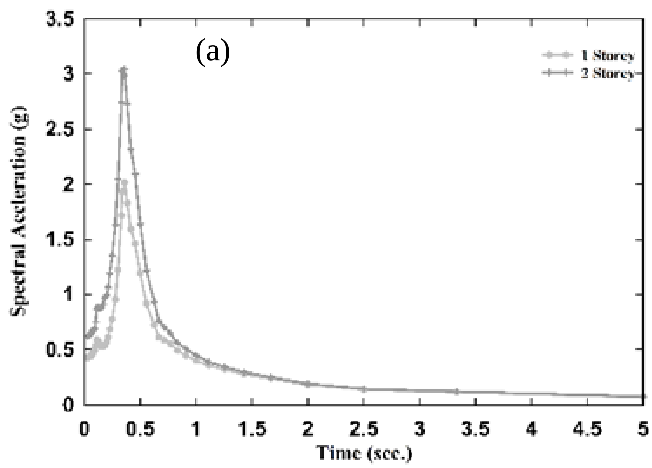
Chi-chi 22 (TCU075)	0.2270	149.97	37.37
Chi-chi 23 (CHY028)	0.201	119.976	31.64
Chi-chi 24 (TCU078)	0.2596	119.976	36.688

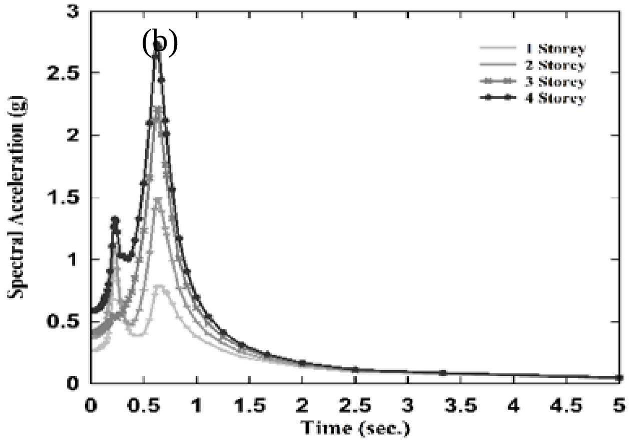
In these tables, T represents the total recorded period and T_p represents the time when peak acceleration occurs.

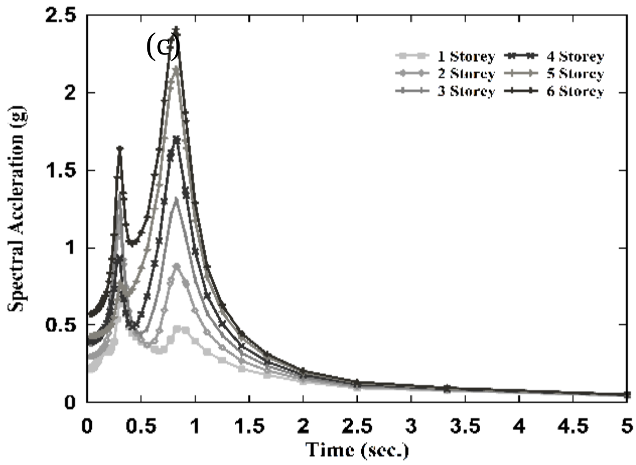
4.5 RESULTS AND DISCUSSION

4.5.1 Floor Spectral Acceleration

In order to perform the dynamic analysis, selected horizontal time history is applied at a different level for each model. For obtaining the floor spectral acceleration, ground acceleration with 5% damping is considered in the present work. The mean spectral acceleration of each model for the ground motion range of 0.2g to 0.32g is shown in Figure 4.1. From the figure, it is seen that, as the height of the building increases, the amplification value decreases. It is also observed that for the building period is less than 0.5 sec, the spectral acceleration values are higher.




(b)
1 Storey
2 Storey
3 Storey
4 Storey
Spectral Acceleration (g)
Time (sec.)


(c)
1 Storey
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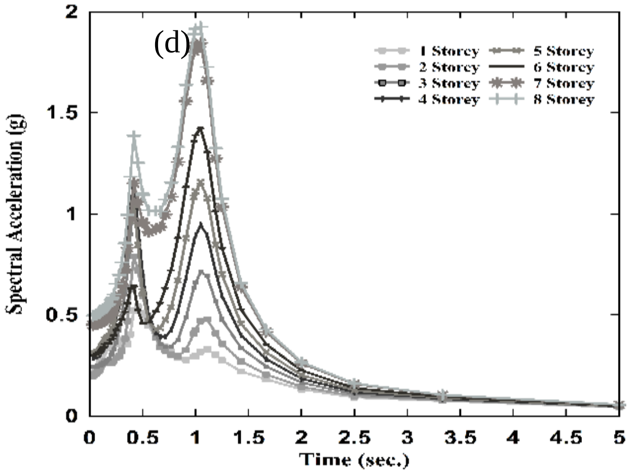
4 Storey
5 Storey
6 Storey
Spectral Accleration (g)
Time (sec.)


(d)
1 Storey
2 Storey
3 Storey
4 Storey
5 Storey
6 Storey
7 Storey
8 Storey
Spectral Acceleration (g)
Time (sec.)

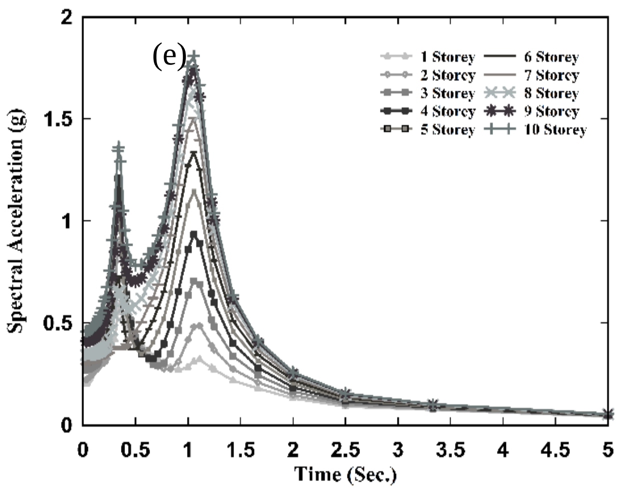


Figure 4.1 Mean floor spectral acceleration for ground motion range 0.2g to 0.31g (a) 2 storey (b) 4 storey (c) 6 storey (d) 8 storey (e) 10 storey

4.5.2 Comparison of Peak Floor Acceleration

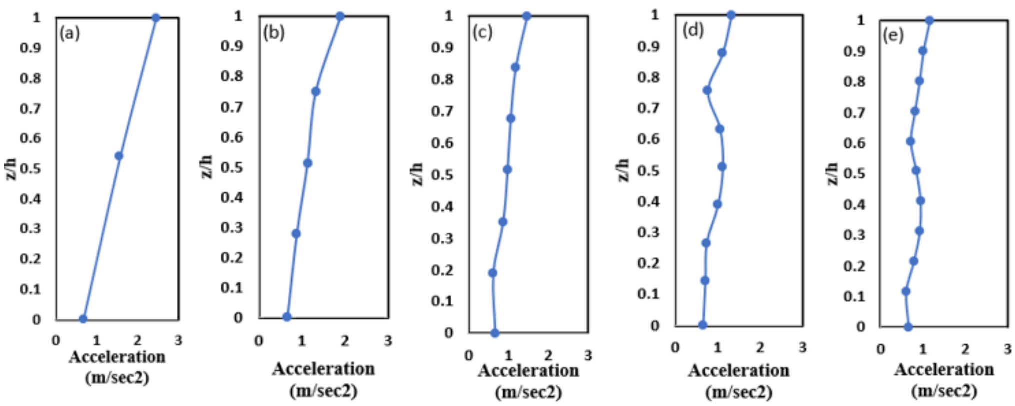


Figure 4.2 Behaviour of floor acceleration for ground motion 0.06g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 storey

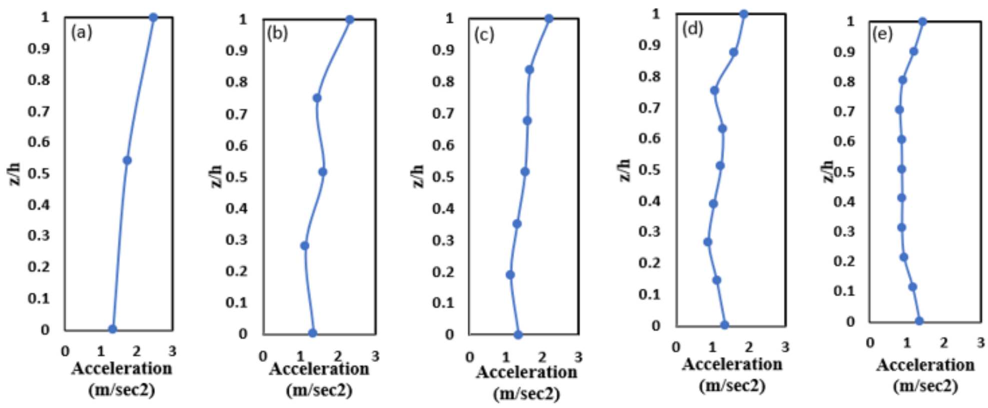


Figure 4.3 Behaviour of floor acceleration for ground motion 0.16g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 stories

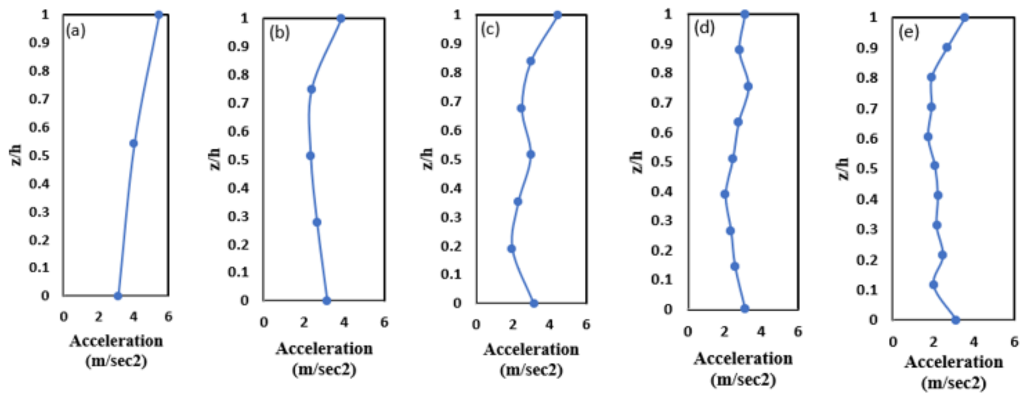


Figure 4.4 Behaviour of floor acceleration for ground motion 0.32g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 stories

The peak floor acceleration is used to define the seismic demands on rigid or semi-rigid (when frequencies of vibration more than 20 Hz) acceleration sensitive NSCs. However, for flexible NSCs, the acceleration is different from the peak floor acceleration. Figures 4.2-4.4 shows the comparison of the 5% damped floor acceleration, for the various heights of buildings during the Chi-Chi earthquake. The PGA of Chi-Chi earthquake time histories are 0.06g, 0.16g and 0.32g, respectively. For the fundamental period of the building is less than 0.5 sec., the peak floor acceleration is approximately 3.5, 2 and 1.5 times higher than the PGA for 0.06g, 0.16g and 0.32g, respectively. However, it is increased as 3, 1.8 and 1.3 times the peak ground acceleration when the building period lies in the range of 0.5 to 1 sec. For higher building period (more than 1 sec), the peak floor acceleration is approximately 2, 1.5 and 1.3 times the peak ground accelerations having PGA of 0.06g, 0.16g, and 0.32g, respectively. Moreover, when the PGA of the ground motion increases, the peak floor acceleration decreases. It is also observed that when the building period increases, the peak floor acceleration decreases.

4.5.3 Effect of Building Period on Amplification Factor

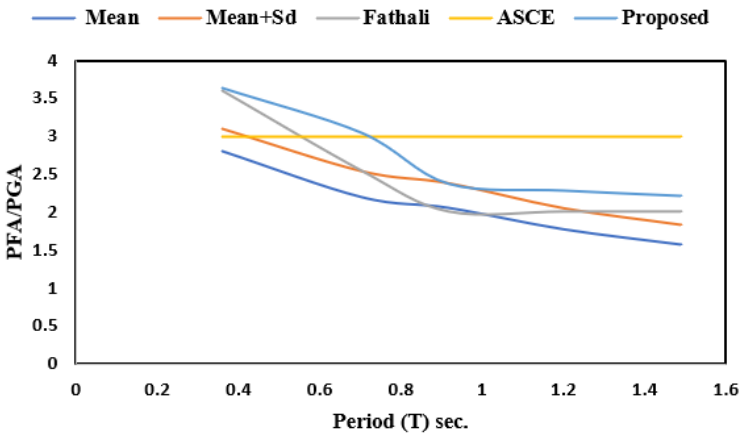
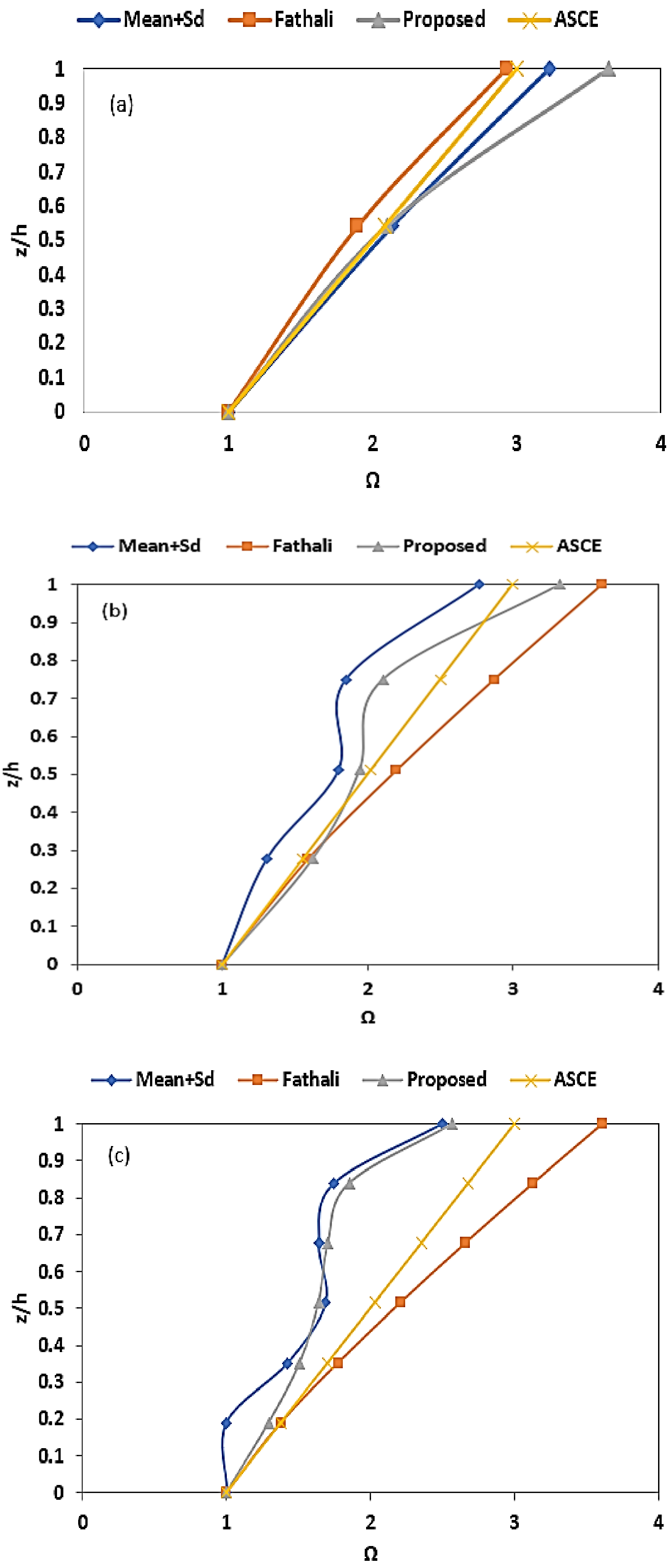


Figure 4.5 Comparison of building period to PFA/PGA with different models

Based on linear time history method, the acceleration amplification factor depends on the fundamental period of the building. Figure 4.5 illustrates the mean and Mean + SD of PFA/PGA for each of the five buildings. From comparison of the PFA/PGA values with ASCE code, it is observed that PFA/PGA values are constant for various natural periods of structures for ASCE model. However, Fathali's model showed that the PFA/PGA values are not consistent, and its values are different for different building period.

4.5.4 Comparison of the Amplification factor with different models

Comparison with the proposed model, ASCE, Fathali's non-linear mathematical model and the Mean + SD results, are shown in Figure 4.6,4.7 and 4.8 respectively.


Mean+Sd
Fathali
Proposed
ASCE
(a)
(b)
(c)
z/h
Ω
0
0.1
0.2
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0.4
0.5
0.6
0.7
0.8
0.9
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2
3
4

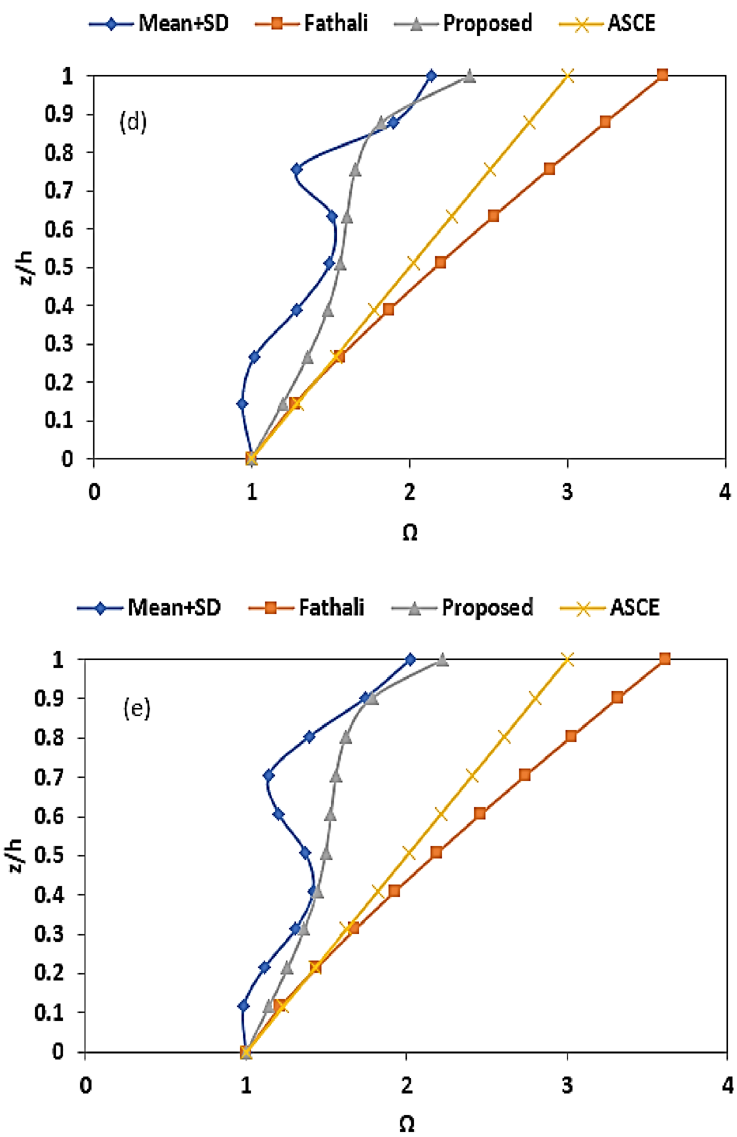
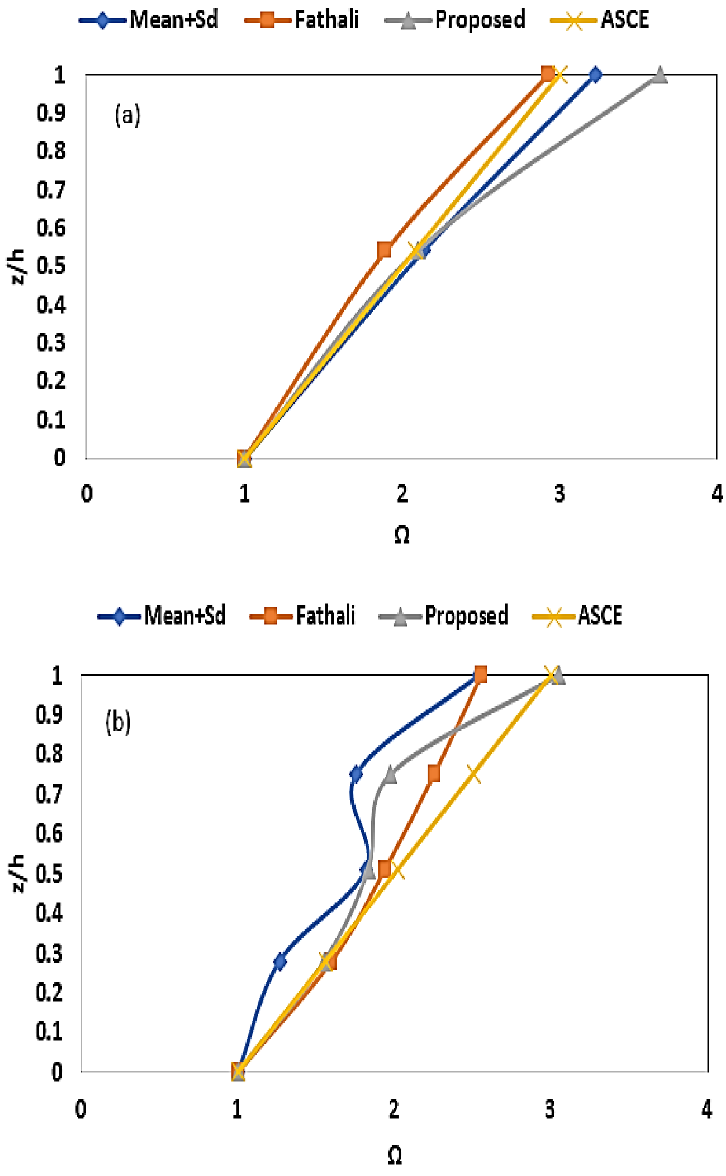
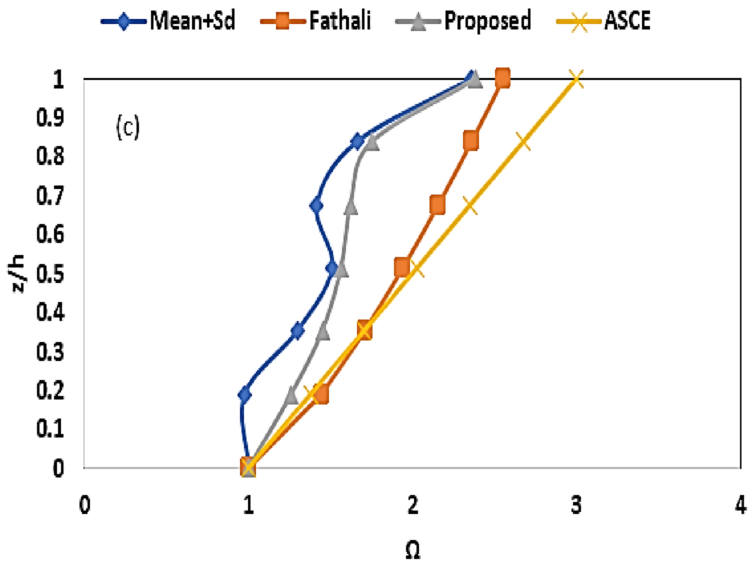


Figure 4.6 Comparisons between acceleration amplification factor to normalized height when ground motion ranges less than 0.067g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 stories

ASCE amplification model shows linear behaviour as the natural period of the structure increases. For the natural period of the structure less than 0.5 sec, ASCE results observed that its values are 11.0% less than mean + standard deviation (Mean + SD). However, Fathali's model resulted 7.0% less than the amplification factor for Mean + SD results. As the height of the building increases, the ASCE and Fathali's acceleration amplification models achieved conservative results. The proposed amplification model provided the values similar to the Mean + SD results. The shape of the curve from proposed model is also similar to the Mean + SD results as the height of the building increases.




Mean+Sd
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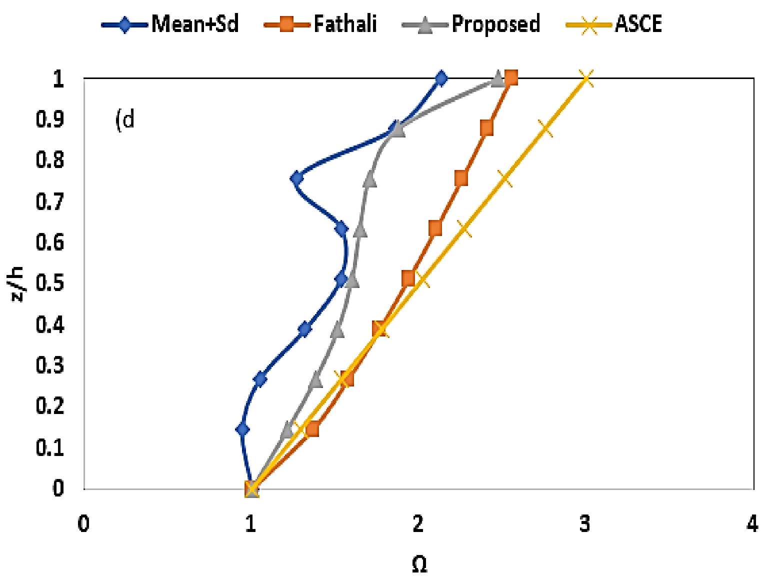
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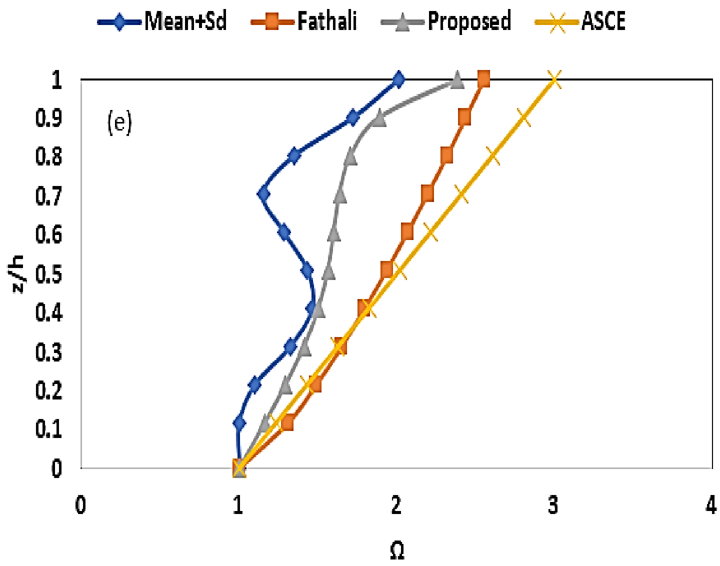
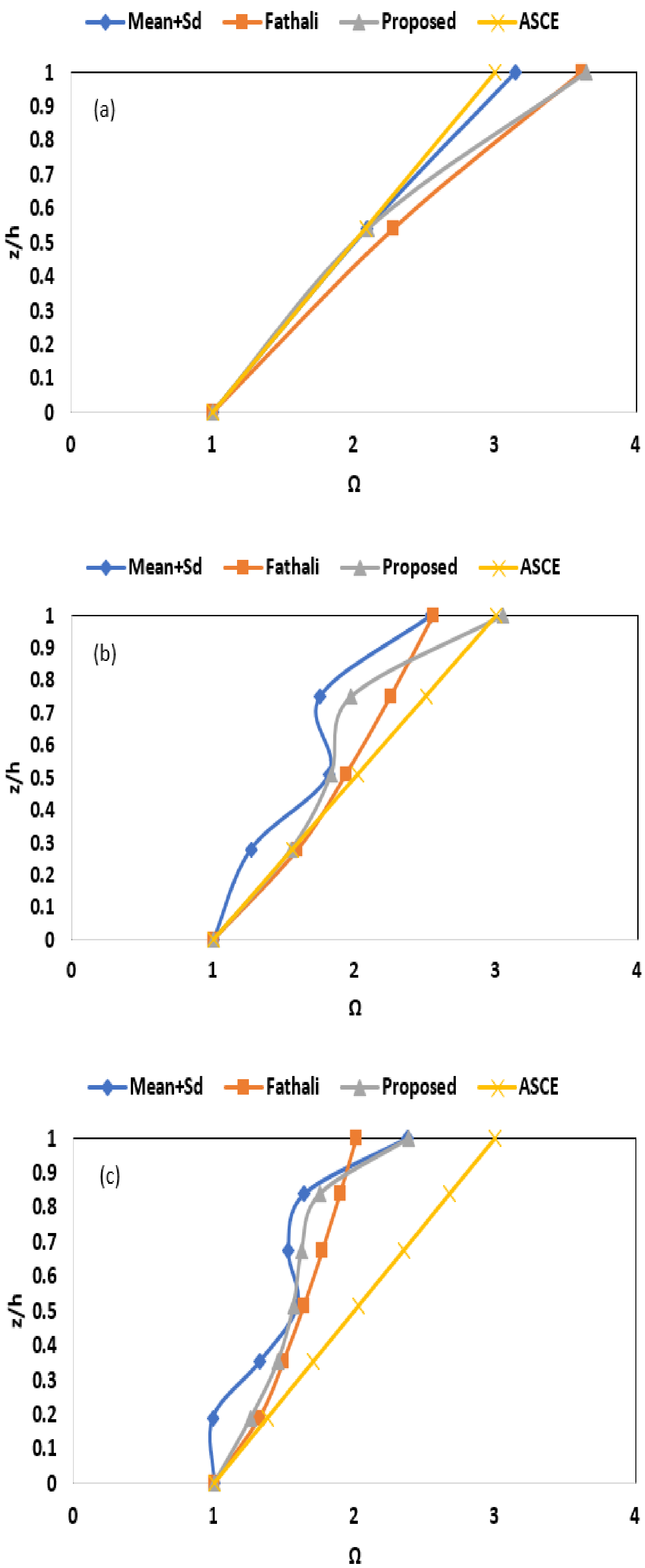


Figure 4.7 Comparisons between acceleration amplification factor to normalized height when ground motion ranges are 0.067g to 0.2g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 stories

For the ground motion range from 0.067g to 0.2g, the Fathali's model overestimated the amplification factors when the normalized height of the building is higher than 0.5. The difference between Mean + SD amplification and ASCE model's amplification values increases as the fundamental period of the building increases. Fathali's and ASCE amplification models are approximate 28% and 50% higher than the Mean + SD results as the natural period of the building increases up to 1.5 sec. Though, the proposed amplification model obtained values 15% higher than Mean + SD results. The performance of the proposed model is similar to the Mean + SD amplification results.


Mean+Sd
Fathali
Proposed
ASCE
(a)
(b)
(c)
z/h
Ω
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0.7
0.8
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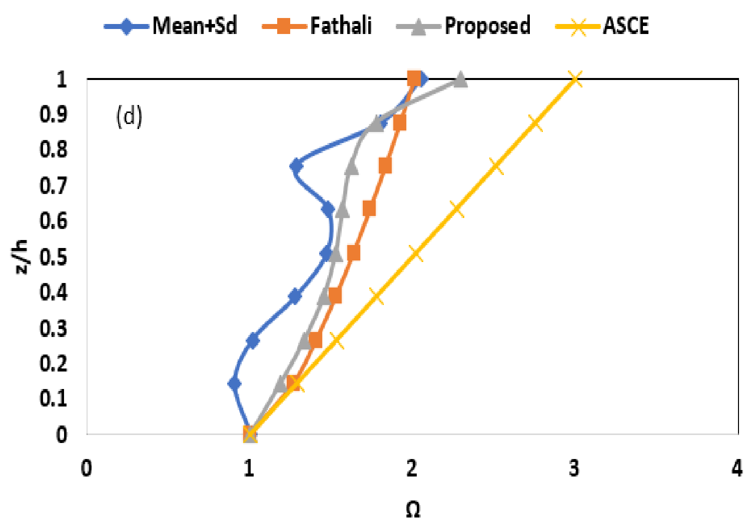

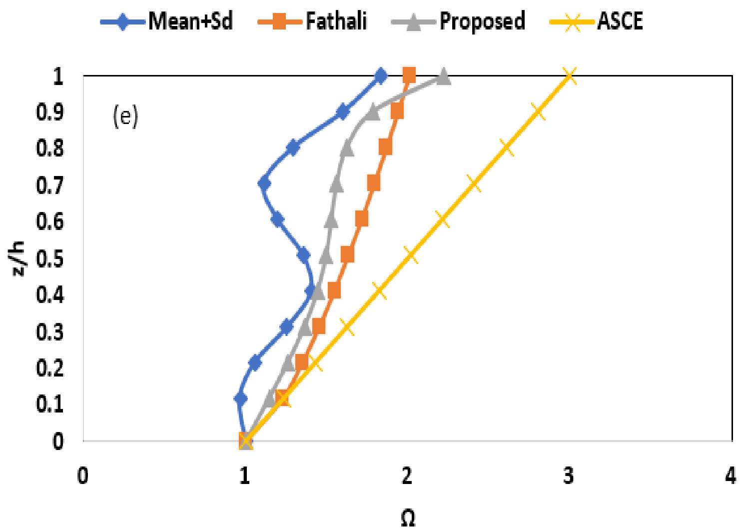

Figure 4.8 Comparisons between acceleration amplification factor to normalised height when ground motion ranges are 0.2g to 0.32g (a) 2 (b) 4 (c) 6 (d) 8 and (e) 10 stories

When the ground motion range is between 0.2g to 0.32g, the amplification values of the Fathali's model is around 15% higher than the Mean + SD results. For this ground motion range (0.2g to 0.32g) Fathali's model gave better results, but the deviation from Mean + SD results increases as the normalized height goes higher than 0.5. As the fundamental period of the building rises, the amplification values of Mean + SD falls. However, ASCE model observed that amplification factor varies linearly as the height of the building increases and its maximum values at the top of the building is 3. The amplification factor results obtain by ASCE code is approximate 60% higher than the Mean + SD results. The results observed by the proposed model is approximately 10% to 20% higher than Mean + SD results. The behaviour of the proposed model is very close to the behaviour of Mean + SD results, respectively.

4.5.5 Comparison of Component Amplification Factors

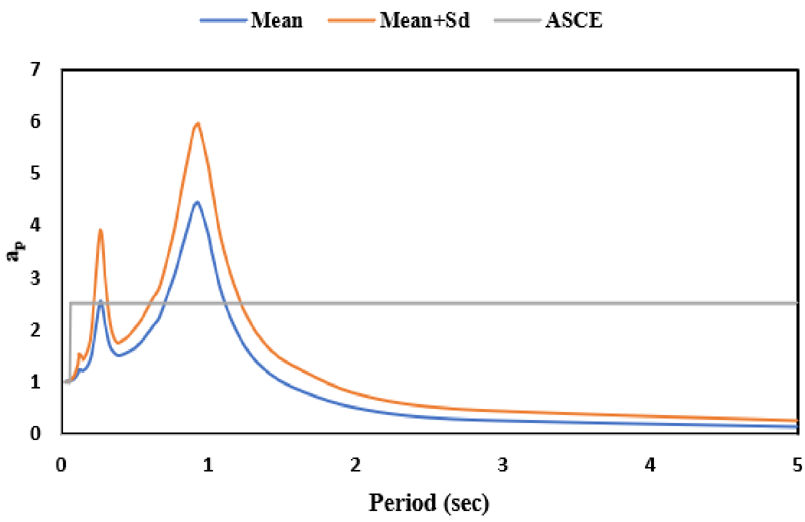

Figure 4.9 Comparison of actual and ASCE ap spectra based on 30 floor acceleration histories recorded in 4 Storey building under earthquakes with PGA > 0.2 g.

The component amplification factor (a_p) refers to the dynamic amplification of NSCs compared to PFA. ASCE code defines a_p is 1 for rigid components (those components having a natural period less than 0.06 sec.) and 2.5 for flexible components (those with a natural period higher than 0.06 sec). From figure 10, it is observed that the code values gave conservative results when the component period is higher than 0.25 sec. For flexible components, a_p values observed from the Mean + SD component amplification results are approximately 2 to 2.5 times higher than the ASCE codal results.

From the comparison of the proposed model and the previous research model, it is found that the ASCE amplification factor formula gives significant results when the period of the structure is less than 0.5 second. ASCE formula provided conservative results when the period of the structure higher than 0.5 seconds. Fathali's model notifies better results as compared to the ASCE code when the ground motion acceleration range is between 0.067g to 0.32g. The difference of amplification values between the Mean + SD and Fathali's model results are increasing between the ground motion range of 0.01g to 0.067g, respectively. However, the proposed model gives more realistic results compared to the other models.

4.6 CONCLUDING REMARKS

In this paper, five moment-resisting RC frame models having different heights are considered. Building frames are analysed using linear time history method, with an observed large number of time history data having ranges less than 0.067g, 0.067g to 0.2g and 0.2g to 0.32g respectively. To get the actual PFA and PGA values and with the help of these data, a non- linear acceleration amplification formula is proposed and compared with the previously reported models. It is found that:

- ASCE formula provides better results when the period of the structure is less than 1.0 second. After that, it performed conservatively.
- The Fathali's model showed promising results to ASCE. It gave obscure results when ground motion lies 0.01g to 0.067g.
- In many cases, the Fathali's model provide better results at the roof of the building, but for other storeys, it is less satisfactory.
- The shape of the amplification factor obtained by the proposed model is close to the shape of the Mean + SD results.
- The a_p values given by the ASCE is conservative and its values are 2 to 2.5 times lower than Mean + SD results at sometimes.
- On comparing the previous mathematical model, proposed non-linear amplification models give more realistic results to Mean + SD results.