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Influence of Soil Structure Interaction on Seismic Fragility of Reinforced Concrete Building

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ABSTRACT

Effect of Soil-structure interaction (SSI) modelling on seismic vulnerability of reinforced concrete moment resisting frame building is the key objective of the present study. The building situated in Indian seismic zone IV and resting on soft soil has been considered for the study. Three types of foundations have been assigned to example building; fixed base, isolated footing and raft foundation. For SSI effect for the building with isolated footing and raft foundation, a linear spring modelling have been used. Seismic inelastic displacements in these three models have been estimated from static pushover analysis. Spectral displacement based fragility curves have been developed for different damage states. Seismic reaction of building considering SSI modelling is related with conventional fixed base model. It is concluded that for the building resting on soft soil, SSI modelling is the influencing parameter on base shear, drift, ductility and on probability of exceeding the damage state.

Keywords: Seismic vulnerability, fragility curves, nonlinear pushover analysis, Soil structure interactions

1. INTRODUCTION

Seismic fragility curves are the tool to asses seismic vulnerability of existing buildings and several researchers were used it for the estimation of losses due to earthquake (Nazri, 2018). These curves are generated from real earthquake damage data to estimate or predict whether the damage meets or exceeds a certain performance level for a given set of ground motion parameters (Pitikalis et al. 2014). In addition, the curves can be applied to predict both pre- and post-earthquake situations. These curves are unique because every building has specific fragility analysis (Hancilar et al. 2014).

Interactions between three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation are the reason to affect the response of the structure while ground waves excitation (FEMA440, 2009).Soil-structure interaction (SSI) study estimates comprises the effect of a specified free-field ground motion, on the structure, the foundation and the soil conditions around the foundation.

SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. Accordingly, SSI accounts for the difference between the actual response of the structure and the response of the theoretical, rigid base condition (NIST GCR 12-917-21, 2012).

This paper focuses on SSI analysis considering various foundations. The influence of SSI modelling on seismic vulnerability of structure is studied by evaluating fragility curve.

2. ANALYTICAL METHODOLOGY

Menglin et al. (2011) concluded from the research that SSI is beneficial to explore seismic response in true sense. The main focus was to evaluate the effects on SSI on the structural response with consideration of seismic provisions. Mylonakis & Gazetas (2000) concluded that SSI affects on ductility demand of the structure which may either increase or decrease depending on the features of ground motion and structure.

For present study, analytical method based on static pushover is adopted to develop fragility curves. A static pushover method has been used to estimate seismic inelastic displacements in the structure. The direct analysis approach is used for modelling soil in which soil and structure are included in the same model. Winkler model representation is used to assess the effect of soil lying underneath the foundations. Linear springs with six DOF (three translations and three rotations) were assigned for modelling the soil (Saez- 2012, ASCE 41-2017). A parametric study to assess the seismic response of building has been carried out by considering different types of foundations resting on soft soil.

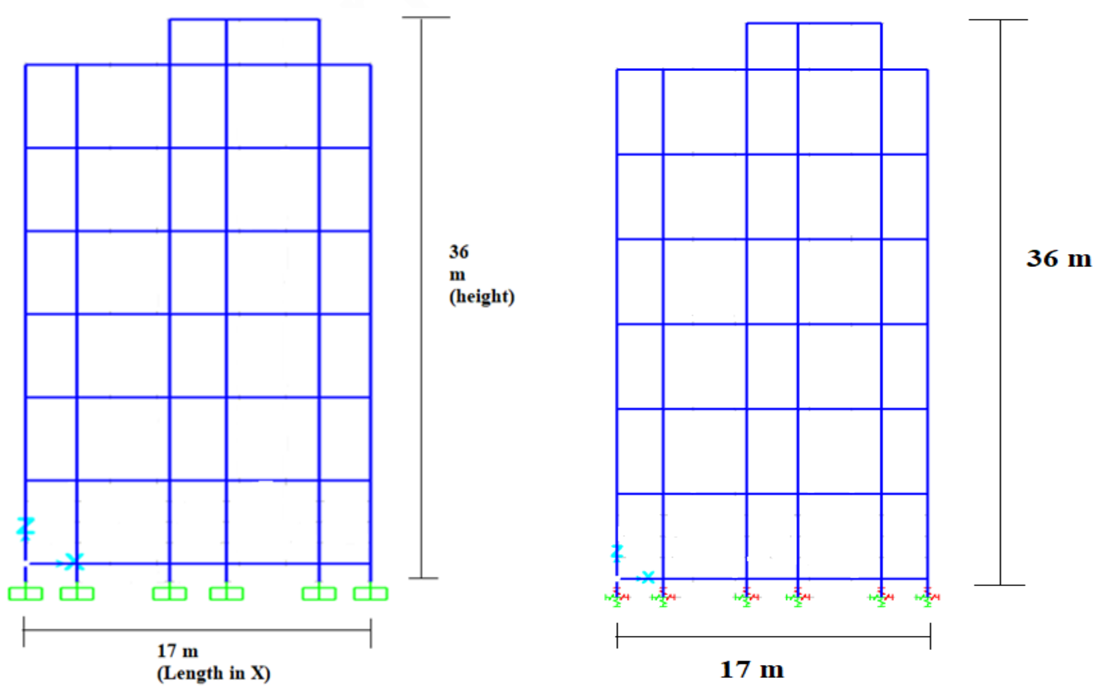

Figure 1. Elevation of model a) building with fixed base, b) building with spring supports

Example Building Model

A 3-D frame building having five stories has been considered. The elevation of it is shown in Figure 1. It is an industrial building having storey height as 5.5m each. An importance factor of 1.5 as per IS 1893-2016 and the building measuring 17 m X 40 m in plan has been used. Figure 2 show the plan of the building. The building is designed as a special moment resisting frame using linear response spectrum analysis and designed for various load combinations specified in the code. Concrete of grade M30 and reinforcement having grade Fe500 have been considered. Table 2 shows the details of column sections. The beam sections are 230X450, 230X600, 230X750, 300X400, 300X500, 300X600, 300X700, 300X750 and 450X750 mm.

Three models have been considered for the study a) Model I- model with fixed base, without SSI b) Model II- model considering SSI with isolated footing at base c) Model III- model considering SSI with raft foundation at base.

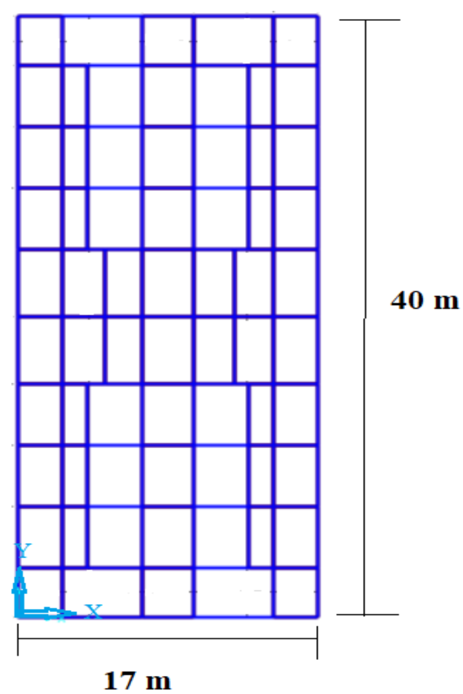

Figure 2. Plan of the building model

Modelling of foundation

Sizes of the isolated footings are mentioned in Table 2. The embedment depth has been assumed to be 2m.Thickness of raft foundation is 200mm. The equations from ASCE 41-2017 have been used to calculated equivalent spring stiffness's. Soil properties in terms of the elastic modulus, shear modulus and Poisson's ratio were considered appropriately in the calculation of equivalent spring stiffness. Table 1gives the soil properties considered for modelling. Table 3 shows the soil spring stiffness values used for both Model II and III**.**

For modelling of isolated footings in Model II, six springs were assigned at the end of the columns as shown in fig. 1b. Raft slab in Model III is modelled as area- spring modelling command in SAP2000v21 software (Raychowdhury, 2008).

Table 1. Properties of soil

Type of soil	Soft soil
Soil bearing capacity	100 MPa
Young's modulus	12000 MPa
Poisson's ratio	0.45
Shear modulus	4137.93 MPa

Table 2. Reinforcement details in Columns

Column	Size in mm	Main reinforcement	Footing size in mm
C1	500X500	12#20ϕ	2250x2250x750

C2	550X550	12#25ϕ	2300x2300x750
C3	600X400	6#25 ϕ and 6# 20 ϕ	2600x2600x850
C4	650X450	12#25ϕ	2700x2700x850

Table 3. Spring stiffness values at foundation

Spring stiffness at foundation	Values(KN/mm^2)
Translation along X direction - K_X	160745.4
Translation along Y direction - K_Y	165040.4
Translation along Z direction - K_Z	232917.4
Rotation along X direction - R_X	2668981
Rotation along Y direction - R_Y	4202134
Rotation along Z direction - R_Z	3721987

3. MODAL ANALYSIS

Modal analysis has been performed to study the dynamic properties of the building, Table 4 shows the result. It has been observed that the time period for model I is less than other models, indicating stiff behaviour resulting conservative design. Mass participation in fundamental mode for all models is less indicating need of higher modes for response estimation. The coupling of modes has been observed. Analysis results are also showing that X direction is weaker.

Table 4. Modal Analysis Results

Model	Fundamental time period (Sec)	Mass participation in fundamental mode (unit less)	
		UX	Rx
Model I	2.04	0.73892	0.10523
Model II	2.14	0.74803	0.10472
Model III	2.13	0.6347	0.1495

Nonlinear modeling of structural elements

As per to structural mechanism concept, ends of beam and column are the likely locations of formation of hinges under lateral loads due to concentration of flexural and shear stresses. Flexural and shear failure of the elements are commonly observed; they are usually addressed by assigning plastic hinges, near the ends of the element, one is flexural hinge and other is shear hinge.

As the building considered under study is modelled according to IS1893 and IS 13920 revised code; it is safe guarded for shear and hence there is no need to assign shear hinge for the beam and column sections as well as joint section. Flexural hinges of M3 and P-M2-M3 DOF have been assigned to beams and columns respectively. In SAP2000, these hinges can be assigned directly using auto-hinge option. Slab has been assigned with rigid diaphragm. Geometric nonlinearity has been considered by incorporating P-delta effect. Contribution of brick masonry infill in resisting lateral loads has neglected. Nonlinear Pushover analysis (POA) has been performed to develop seismic fragility curves. A capacity spectrum method has been used to estimate seismic performance and vulnerability of the structure.

4. PUSHOVER CURVES

Pushover curves for the model I, II and model III were obtained from POA. These curves along X and Y directions are shown in Figures 3 and 4. The base shear of the structure is affected by different foundations considered. Base shear for the model I is comparatively higher than other two models indicating higher lateral resisting capacity. The roof displacement of the building increases by 11% for model II and III. Thus by consideration of SSI, the behaviour alters from stiff to flexible.

Table 5. Base shear at performance point

Model	Base Shear (KN)	
	X- Direction	**Y-Direction**
Model I	7511	5770.162
Model II	6905	5524.618
Model III	7143	5593.397

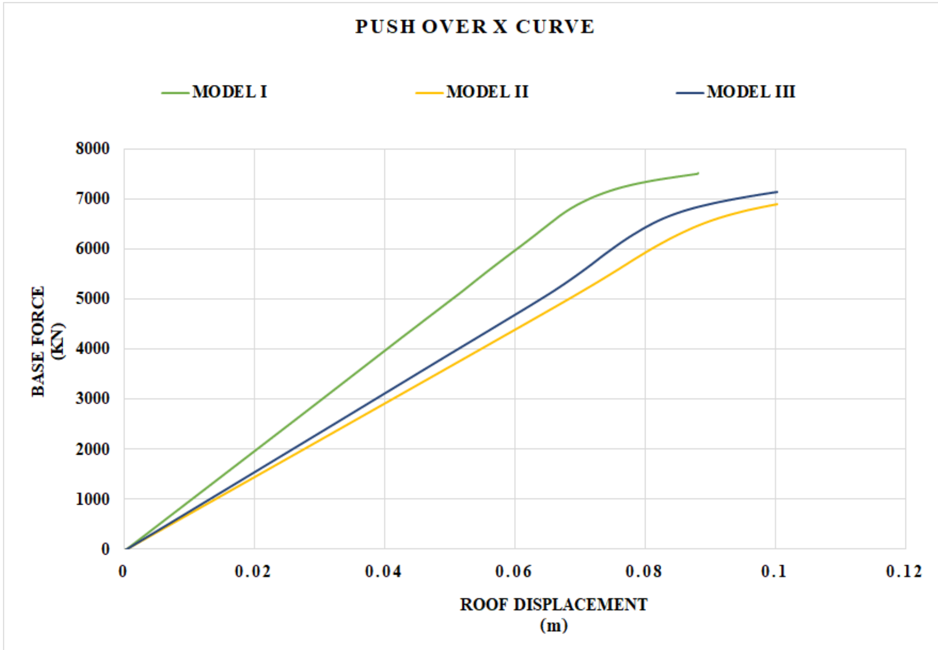

Figure 3. Push over curve in X- direction

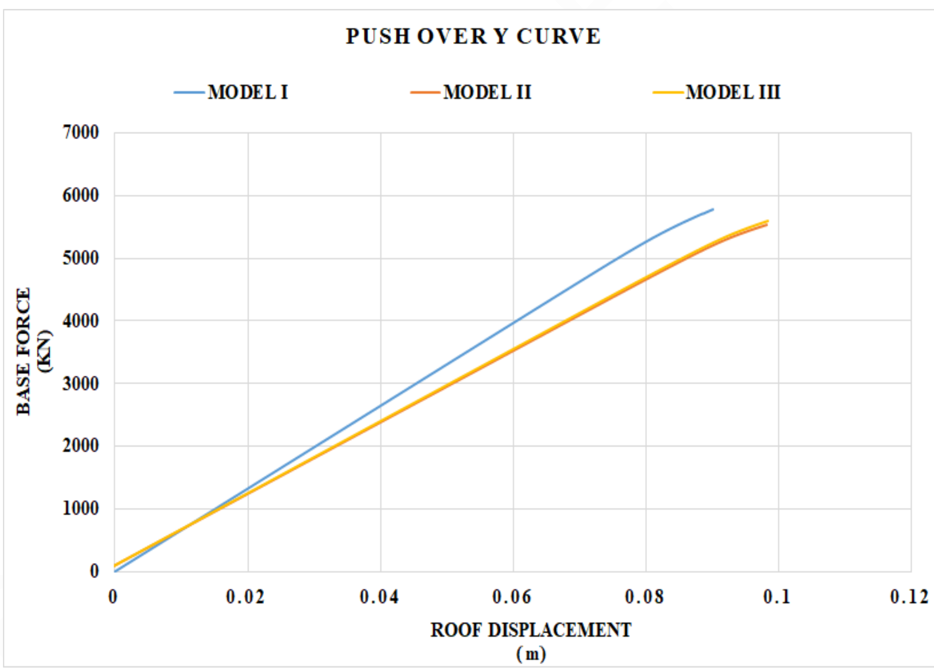

Figure 4. Push over curve in Y- direction

Drift and Ductility

Based on the POA results, inter storey drift are calculated for model I, model II and model III. Corresponding graphs in X and in Y directions are as shown in Figures 5 and 6 respectively.

It has been seen that the storey drift increases for model II and model III by 6 times. Model III having raft footing has comparatively less drift than model II. It shows that in soft soil conditions, isolated footing (model II) is more susceptible to damage then raft footing (model III). Pushover curve is converted into bilinear curve (ATC40-1996). The ductility factor of model I, II and III were calculated from bilinear curve as a ratio of ultimate displacement to the yield displacement. Table 6 shows the result. The ductility of structure increases in model II and model III due to consideration of SSI effects.

Table 6.Ductility factor

Model	Ductility factor in X-Direction (Unit less)
Model I	10.96
Model II	12.20
Model III	11.83

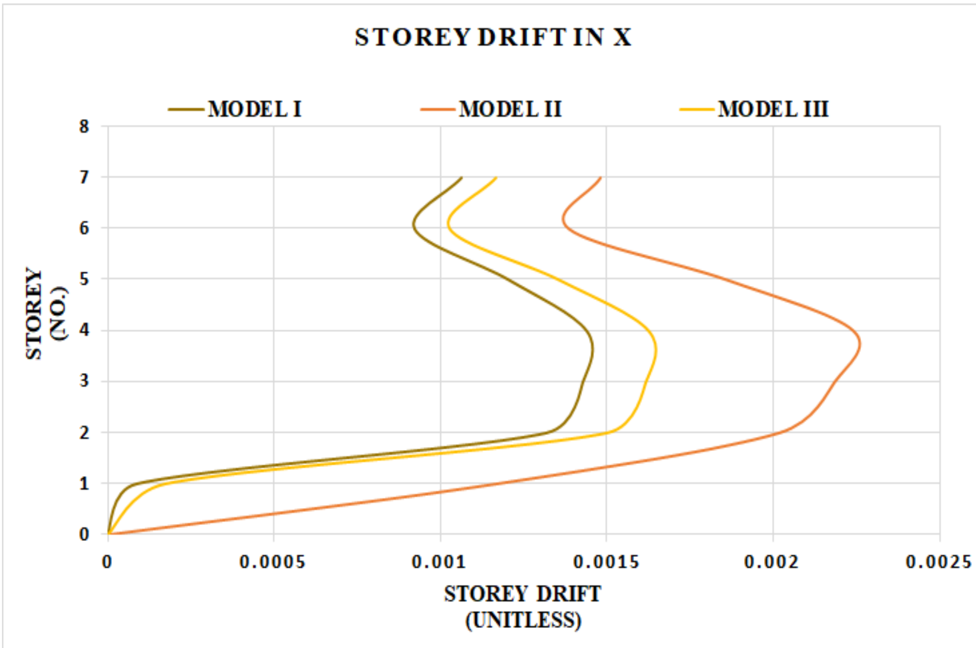

Figure 5.Storey drifts in X- direction

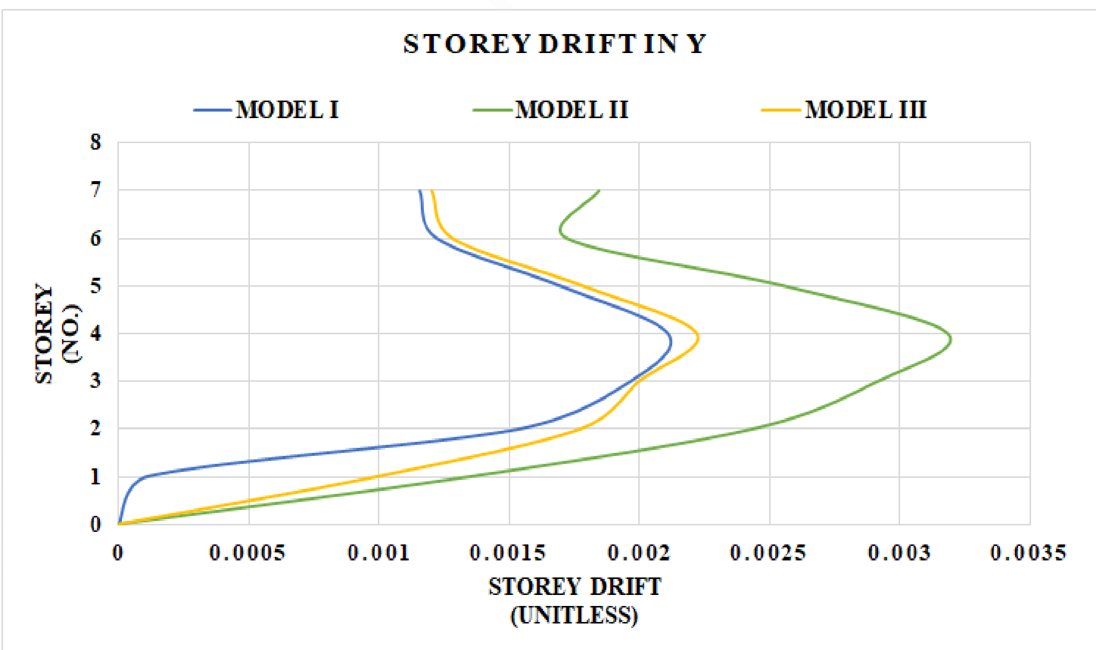

Figure 6.Storey drifts in Y- direction

Damage Pattern

The damage pattern has been studied for three models by POA at performance point, number of hinges developed in the structure is shown in Table 7. At performance point, the number of hinges developed in model I are in advanced state than model II and III. Thus the assumption of fixed base shows conservative performance.

Table 7. Hinge states at performance point

Model	Direction	Number of hinges					
		A TO B	B TO IO	IO TO LS	LS TO CP	CP TO C	Total
Model I	PUSH X	596	550	778	590	0	2514
	PUSH Y	567	232	934	781	0	2514
Model II	PUSH X	1779	409	217	109	0	2514
	PUSH Y	1784	207	310	213	0	2514
Model III	PUSH X	1409	458	416	231	0	2514
	PUSH Y	1397	201	577	339	0	2514

5. FRAGILITY ANALYSIS

Fragility curves are defined as the probability of the exceedance of the given damage states $d_{si,}$ for the spectral displacement of the structure, which ultimately shows the vulnerability of the structure.

A fragility curve is well described by lognormal probability density function shown by eq.1 (HAZUS MH MR4 -2003).

$$P(d_{si}/S_d) = \emptyset\left[\frac{1}{\beta_{dsi}}\ln\left(\frac{S_d}{S_{d_{si}}}\right)\right] \quad (1)$$

Where $Sd_{si}$is the threshold spectral displacement at which the probability of the damage state ds_i is 50 %, β_{dsi} is the standard deviation of the natural logarithm of this spectral displacement, ∅ is the standard normal cumulative distribution function. The damage states threshold is calculated using the equations shown in Table 8.

The fragility curves were plotted using the data from capacity spectrum analysis. The pushover curve is idealized into bilinear curve as per FEMA 356-2000 coefficient method. The spectral displacement at yield and ultimate point were obtained from bi-linear curve.

Damage state definition

Building damage functions are in the form of lognormal fragility curves that relate the probability of being in or exceeding. Four damage states (DS) have been considered in present study; slight damage (SD), moderate damage (MD), extensive damage (ED) and complete damage (CD). Damage state thresholds $(S_{d_{si}})$ $f$or each DS, median threshold value of S_d has been estimated from Figure 7. Table 8 shows estimated median values for each state.

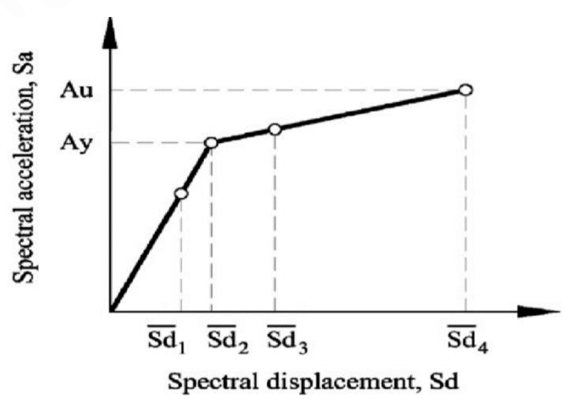

Fig 7 Damage State thresholds for capacity spectrum (Barbat et al 2008)

Table 8 Damage state thresholds $(S_{d_{si}})$

Damage state thresholds	Damage state
Sd_1= 0.7Dy	Slight
Sd_2 = Dy	Moderate

Sd_3 = Dy+0.25(Du-Dy)	Severe
Sd_4 = Du	Complete

Estimation of fragility curve parameters

Fragility analysis has been carried out for weaker direction (X-direction). Median spectral displacement ($S_{d_{si}}$) estimated values are shown in Table 9.The total variability (β_{dsi}) value is taken from HAZUS (2003) manual.

Table 9. Estimated parameters of fragility curves

Damage states	Median parameter($S_{d_{si}}$) (cm)			Variability parameter (β_{dsi})(cm)
	Model I	Model II	Model III	
	X-direction	X-direction	X-direction	For X direction
Slight	0.0518	0.055386	0.05458	1.6764
Moderate	0.074	0.079123	0.077972	1.6256
Extensive	0.2584	0.29317	0.295157	1.7018
Complete	0.8117	0.93523	0.93972	1.9812

Fragility curves and discussion

The fragility curves were developed for three models. Figures 8, 9 and 10 shows the fragility curves for model I, II and III respectively. The Table 10 shows the comparison of probability of exceedance for collapse damage state at 2 cm spectral displacement.

Table 10. Probability of exceedance at 2 cm Spectral displacement

Model	Probability of exceedance (%)			
	SD	MD	ED	CD
	X-Direction	X-Direction	X-Direction	X-Direction
Model I	98.53%	97.8 %	88 %	67 %
Model II	98.38 %	97.6 %	87 %	64.9 %
Model III	98.4 %	97.7 %	86.95 %	65 %

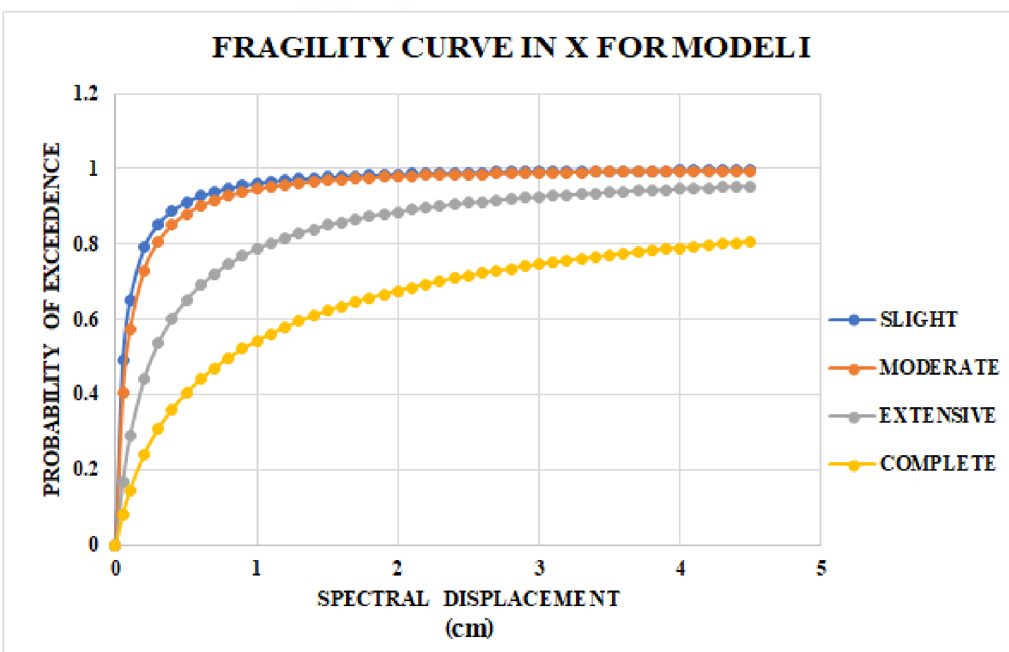

Figure 8. Fragility Curve in X – Direction for Model I

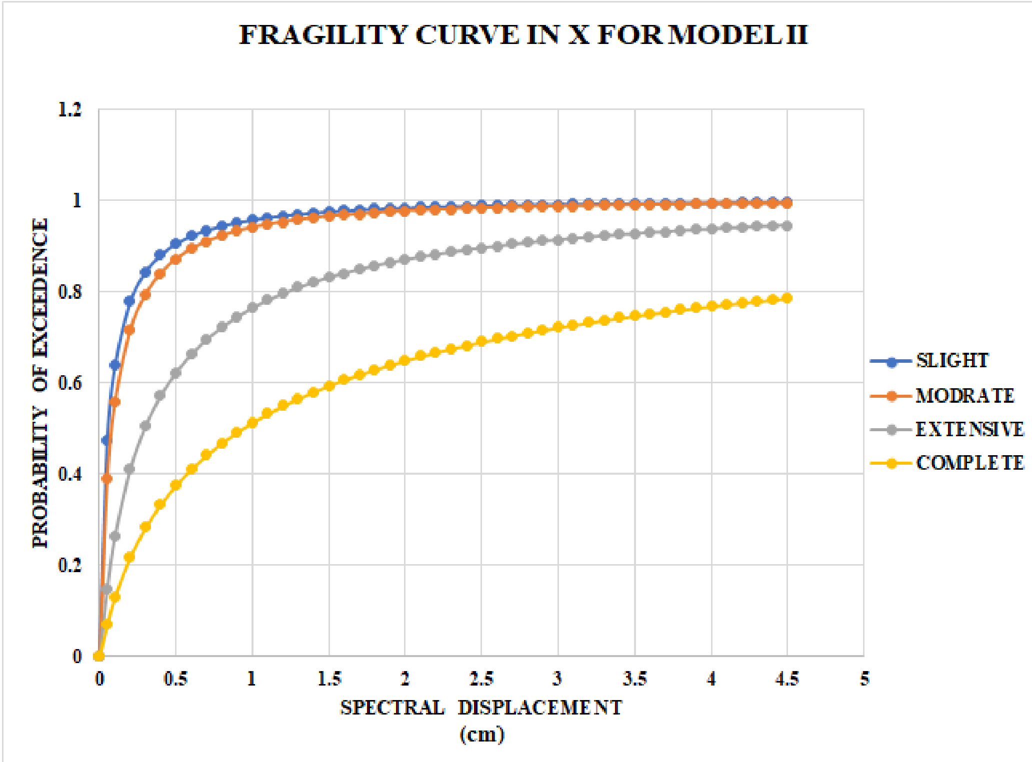

Figure 9. Fragility Curve in X – Direction for Model II

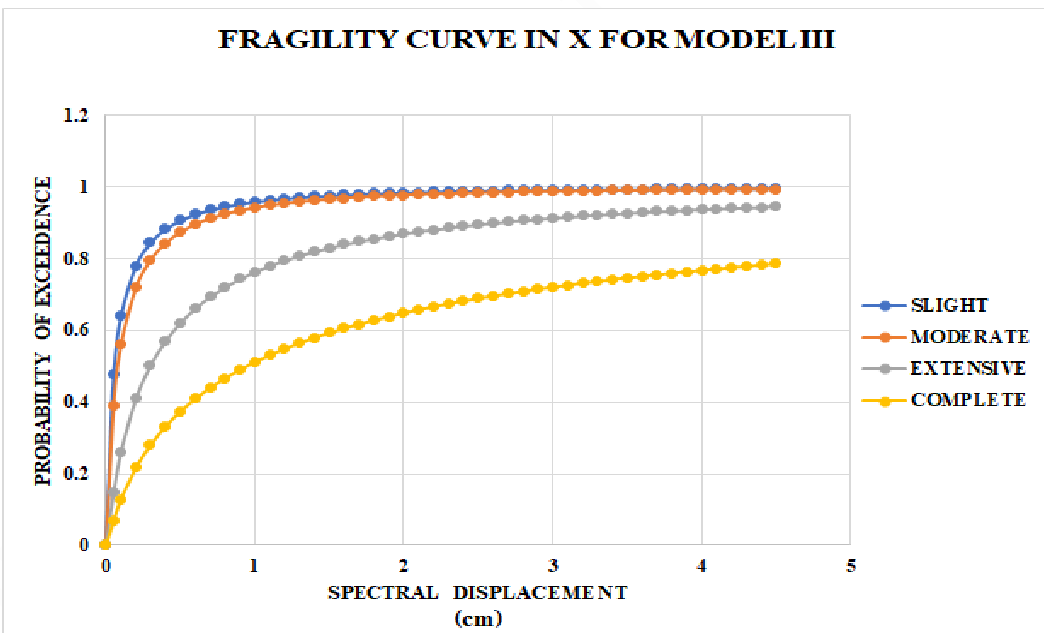

Figure 10. Fragility Curve in X – Direction for Model III

6. CONCLUSION

Due to SSI following effects are seen:

a) Roof displacement increases by 6 times for models with SSI effect than fixed base model.
b) Base shear decreases by 4.8 times for models with SSI effect than fixed base model.
c) Time period increases by 4.9 times for models with SSI effect than fixed base model.
d) Inter-storey drift increases by 6 times for models with SSI effect than fixed base model.
e) Ductility increases by 7.9 times for models with SSI effect than fixed base model.

f) Probability of exceedance for fixed based model is higher in ED and CD state than models with SSI effect

Concluding remark

This study proved the importance of consideration of soil-structure interaction on performance-based design of buildings and the raft foundation gives quite similar results to fixed base rather than isolated footing. Economic design can be achieved by including SSI effects in seismic design. Study recommends SSI modelling for the structure resting on soft soil since it is realistic case.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Peer-review

External peer-review was done through double-blind method.

Data and materials availability

All data associated with this study are present in the paper.

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