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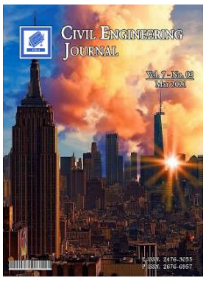

Experimental and Numerical Studies on Setback Buildings Considering the SSI Effect under Seismic Response

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Abstract

From the previous studies it is observed that due to the effect of the earthquake, several irregular buildings failed vulnerably. Further the effect of sub soil conditions where these buildings have been founded also play an important role on the seismic response of these buildings. In the past, experimental studies on the seismic response of different setback building configurations have not been carried out. Therefore, in the present study the seismic behaviour of setback buildings considering Soil Structure Interaction (SSI) has been evaluated by conducting experimental and numerical investigations. Buildings with various setback configurations were considered and are designed as pile foundation supported structures. The irregularity index of these building configurations have been determined as per the existing codal provisions. These piles supported buildings representing the prototype structure have been scaled down according to geometric, kinematic and dynamic scaling laws. The scaled building models are subjected to vibrations beyond resonant frequencies using shake table facility. A comparison of the results has been made between experimental and numerical investigations. Based on the study it has been observed that storey displacements of building with regular configurations are higher in comparison with the setback buildings. It is also found that asymmetrical and symmetrical setback buildings having different irregularity indices as per IS:1893-2016 indicate nearly the same displacements at resonant frequencies.

Keywords: Scaled Model; Prototype; Resonance; Setback Building; Soil Structure Interaction; Irregularity Indices.

1. Introduction

Many Stepped buildings which are vertically irregular in nature have been constructed in order to improve the aesthetic view; these vertically irregular buildings are commonly called as setback buildings. Setback buildings have vertically discontinuities with respect to geometry, due to these sudden reductions in plan along the elevations cause vertical discontinuities that could affect performance of such buildings due to seismological effect, based on the limit condition or the seismic intensity level assumptions, as observed by Michalis et al. (2006) [1] in their analytical study. In order to examine the state of structure during seismic disturbances, Ismaeil (2018) [2] carried out pushover analysis on structures and stated that in pushover analyses, inertia forces' distribution was assumed to be constant in an earthquake, but in reality, as the earthquake severity increases, the distribution changes.

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Previous earthquakes have demonstrated that buildings with setbacks show poor seismic resistance even though having designs in accordance with the seismological code requirements [3]. An analytical study carried out considering linear static analysis, on the influence of vertical irregularity on multi-storey structures subjected to dynamic loading, found that torsional response occurred on account of vertical irregularity [4]. Comprehensive review of various structure due to presence of irregularities in buildings is presented by Satish et al. (2019) [5], they inferred that it is difficult to quantify the irregularity in a setback building with any single parameter in a three-dimensional setback building. Rahman et al. (2013) [6] performed linear static and dynamic analysis on G+10 vertically irregular setback structures, and storey deflection, drift, and shear of the structure were determined. It was seen that stiffness irregularity creates structural instability and major storey shear. This review of various kinds of irregularities indicated that seismic response varies dramatically near irregularities.

Further, sub soil which supports the structures with setbacks also intensifies the response of the structures due to seismic action. Many researchers from their study observed that soil structure interaction is majorly affected by the soil characteristics. Researchers believe that the dynamic nature of the soil and its interaction with the structure can significantly change the building's seismic response. Several analytical, numerical and experimental studies have been conducted on the dynamic assessment of Soil-Structure Interaction (SSI) issues during seismic excitations [7-9].

2. Literature Review

Considerable advances have been made in structural dynamics and seismology of late, as a result of which numerous analytical and experimental methods have been devised to build a more practical model by introducing model complexities like SSI and torsional coupling [10-12].

In order to observe seismic behaviour of three-dimensional buildings considering SSI effects, Farghaly et al. (2013) [13] used SAP2000 package and observed that SSI detrimentally affects the building's seismic response. However, the analysis is valid for structures symmetrical in the X and Y axes. Assuming soil profile supporting the structure to be uniform and having the uniform shear wave velocity. Torabi and Rayhani (2014) [14] carried out seismic analysis on structures and noted that rigid and slender buildings are very prone to SSI influences, i.e., there are changes of natural frequency, swaying of foundations, and higher base shear requirements. Lu et al. (2016) [15] stated that SSI can significantly reduce the ductility and strength requirements of multi-storied structures, particularly those having lesser slenderness ratio and ductility requirements.

Zhou et al. (2009) [16] carried out shake table test on a multiple – tower RC steel frame building which was scaled with a scale factor of 15. This building was subjected to a low, moderate, and severe seismic activity. Li et al. (2012) [17] carried out experimental studies using shake table facility for a scaled model of 1:15 of a twelve-storied casted RC frame with a pile group base sunk into the soil, this model was subjected to varied seismic scenarios for identifying their dynamic reaction. Further experimental results were compared with numerical results and are found to be in good correlation. Hosseinzadeh et al. (2004) [18] observed the behaviour of scaled model due to the influence of soft soils on the seismic response features of single model alone and also the effect of other neighboring steel model structures using a scaled model of 1:100 using shake table facility.

Tabatabaiefar et al. (2014) [19] studied the response of a 15-storied concrete structure erected on comparatively softer soil using numerical simulation, for experimental studies the same building has been scaled down by 1:30. From there studies they observed good agreements between numerical and experimental studies. Hokmabadi et al. (2015) [20] carried out experimental studies using shake table and three-dimensional numerical simulations to investigate the influence of soil-pile-structure interaction (SPSI) on the seismic response of mid-rise moment resisting buildings supported by end-bearing pile foundations. They used scaled model of size 1:30. From their study they inferred that soil-structure interaction induces significant increase in the lateral deflections and inter-storey drifts of the structures.

Goktepe et al. (2019) [21] performed experimental studies on the scaled model of framed RC building resting on a sandy soil with shear wave velocity of 536 m/s and unit weight of 12.9 kN/m^3. For experimental investigations, the realistic site and building structures were scaled with a geometric scaling factor of 1:45. From their study, they concluded that dynamic parameters for scaled model of a single layer soil, restricted with base-rock, have been compared numerically with the proposed laminar soil container, to provide a good agreement. Hirave and Kalyanshetti (2018) [22] carried out experimental and numerical study on three RC scaled building frames with steel bracing system incorporating the effect of soil flexibility. From their study, they inferred that steel bracing system is beneficial to control soil structure interaction effect. Thus, it is seen that many numerical studies have been carried out on setback buildings for assessing their seismic response. But there is a lack of experimental and numerical studies considering SSI effect on different configured setback buildings which can provide some good insights for future designs of setback buildings.

Hence, the objective of this study is to evaluate the seismic response of a five-storied setback RC irregular building considering SSI, both numerically and experimentally. The building was erected on very soft soil with density 1470 kg/m^3 using pile foundations. The structure, soil, and pile foundation were scaled down applying scaling laws. The scaled building models were subjected to sinusoidal vibrations at resonant frequencies using a shaking table facility. Resonant frequency, storey displacement, storey drift and structural damping were determined. The methodology of the research is indicated in Figure 1.

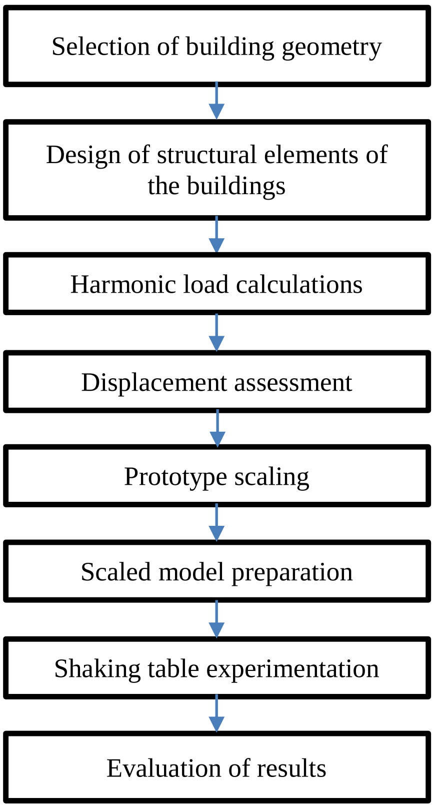


Figure 1. Research methodology

3. Geometric of Structures

The soil structure interaction of five-storied M25 grade RC buildings having vertical irregularities are studied when subjected to sinusoidal ground motion, both experimentally and numerically. Further, a comparative assessment was made in terms of story displacement and story drift. Figure 2 shows the geometries of the buildings considered along with their plan at base in Figure 3. Here, RB denotes a regular building and SB denotes a setback building. These irregular buildings have a uniform story height of 3 m.

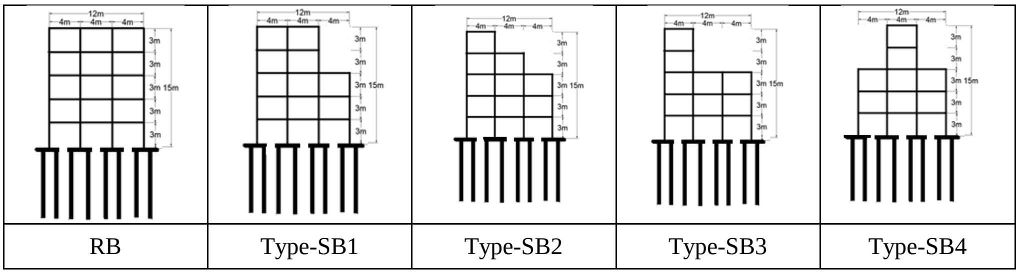


Figure 2. Typical building elevations for five-storey building variants (RB, SB1 to SB4)

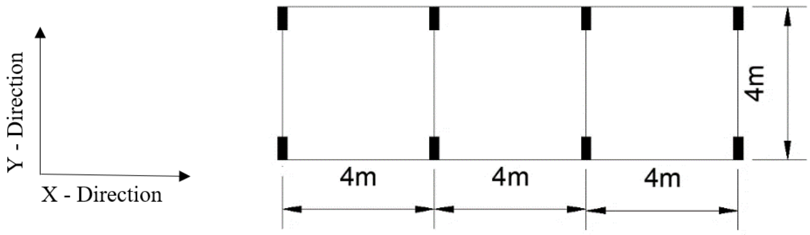


Figure 3. Plan of the building along with column orientation

Vertical irregulates of fixed base setback buildings are categorised according to IS 1893-2016 (Part 1), ASCE 7.05 and Eurocode 8 [23-25]. Table 1 shows comparison of Irregularity indices of setback buildings.

Table 1. Comparison of Irregularity Indices for Setback Buildings

Sl. No.	Building Description	IS: 1893-2016	ASCE 7.05 (2005)	Euro Code-8 (2004)
1	RB	1	1	1
2	SB1	0.33	1.5	0.33
3	SB2	0.66	2	0.5
4	SB3	0.66	3	0.66
5	SB4	0.33	3	0.66

Taking a live load of 3kN/m^2 along with floor finish of 1 kN/m^2 according to IS 875(Part 1 and 2) [26, 27] at each floor and, at roof, live load of 1.5kN/m^2 with floor finish of 2 kN/m^2 is considered in design of RC buildings shown in Figure 1. These buildings are analysed and designed according to IS 1893-2016 (Part 1) and IS 456 [23, 28], the first mode of vibration is obtained along longitudinal direction (X-axis). Table 2 shows the dynamic characteristics of the buildings considered for the present study. The designed details are as shown in Table 3.

Table 2. Dynamic Properties of the Building

Sl. No.	Contents	Description
1	Structure	SMRF
2	Seismic Zone	V
3	Importance factor	1
4	Type of soil	I

Table 3. Details of Structural Elements of the Building

Sl. No.	Contents	Description
1	Slab thickness	150mm
2	Beams dimension	300mm X 400mm
3	Columns dimension	250mm X 600mm

3.1. Scaling of the Prototype Structure

Here, regular building is referred to as prototype and scaled down model is denoted as scaled model. In order to represent investigational model with less degree of distortion, scaling has been carried out according to geometrical scaling, numerical scaling and dynamic scaling whose parameters is as given in Table 4.

Table 4. Scaling Relationships in terms of Geometric Scaling Factor [20]

Sl. No.	Parameters	Scale Factor (S)
1	Mass density	1
2	Stiffness	S^2
3	Force	S^3
4	Modulus	S
5	Acceleration	1
6	Frequency	$S^{-1/2}$
7	Time	$S^{1/2}$
8	Shear wave velocity	$S^{1/2}$
9	Length	S
10	Stress	S

Adopting a suitable geometric scale factor is one of the important steps in scale modelling. For all the models a scale factor of 30 is adopted. According to the scaling laws indicated in Table 4, mass density should be equal to 1. An appropriate and nearest modulus of elasticity of concrete have been adopted and also it has to be help full in fabrication of the model. The mass by volume ratios (mass density) of the prototype to scaled model were considered such that a dynamic similarity was achieved, where the mass by volume ratio of prototype was 339.7 kg/m^3 and the mass by volume ratio of scaled model was 342.1 kg/m^3. Variation in the mass by volume ratio of the prototype and scaled model was found to be 0.67% with the prototype as reference. Table 5 shows the geometric and material properties of the scaled model using scaling laws.

Table 5. Geometric and material properties of scaled model

Sl. No.	Contents	Description
1	No. of stories	5
2	Storey height	0.1 m
3	Bay width (X-axis) each	0.133 m
4	Bay width (Y-axis)	0.133 m
5	Slab thickness	11 mm
6	Size of Columns	2×12 mm
7	Material	Aluminum

Initially both scaled model and prototype are modelled in the FEM based software SAP-2000 by matching frequency and then these models were subjected to Time history analysis using ground motion of 1940 El-Centro(N-S) earthquake. Keeping acceleration values unchanged time step has been scaled down for the scaled model for analysis as per similitude laws($t_m=t_p/\sqrt{30}$) which is as indicated in Table 6. Table 7 illustrate the displacement variation of both scaled models and prototype buildings.

Table 6. Type of loading and scaling of time period

Sl. No.	Type of loading	Prototype		Scaled model	
		Time step (sec)	Acceleration (g)	Time step (sec)	Acceleration (g)
1	El-Centro Earthquake	0.02	0.318	0.00365	0.318

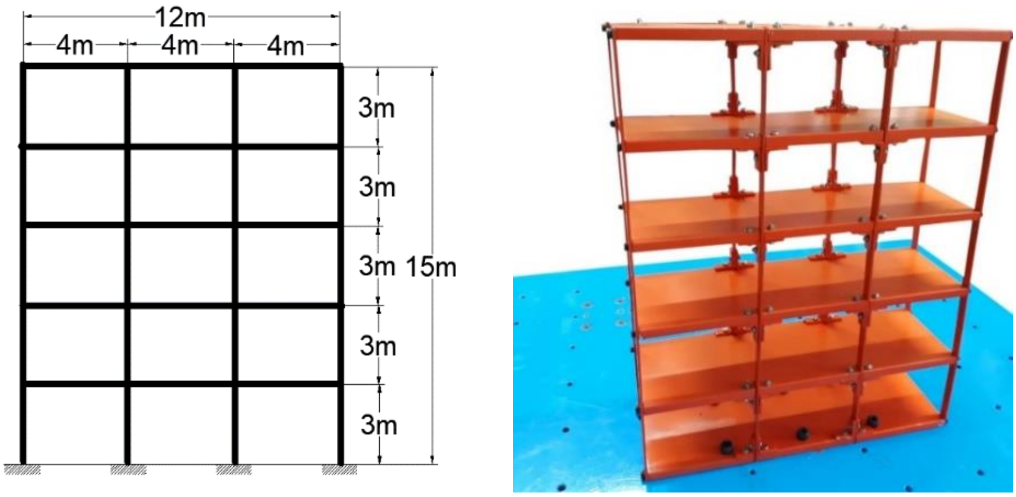
Table 7. Top storey Displacement along longitudinal direction

Sl. No.	Model Description	Resonance Frequency (Hz)	Time period (sec)	Displacement (mm)
1	Scaled Numerical Model	7.53	0.132	2.82
2	Prototype	1.36	0.7335	79.76

From the Table 7 it is observed that by scaling down the time step by $\sqrt{30}$ the displacement of prototype is observed to be increased nearby 30 times of the displacement of the numerically scaled model.

4. Experimental Study

The shaking table facility used (Department of Civil Engineering, UVCE, Bangalore University, Bangalore, India) is a uniaxially driven, and has a table size 1×1 m with a maximum payload capacity of 100 kg. The shaking table has an operating frequency range of 0.05–25 Hz. In the present study, the objective of using the shaking table was to evaluate the change in the dynamic properties of the scaled models for flexible base conditions. In order to get the natural frequency of scaled model (Figure 4), the model was subjected to a gradually increasing unidirectional harmonic excitation (sine sweep wave) with an amplitude in the range of 0.4–1.0 mm and sweep rate in the range of 0.5–15 Hz. The response parameters such as displacements, accelerations and resonant frequencies were recorded by the Data Acquisition System (DAQ).



Type -RB **Scaled Model**

Figure 4. Scaled Model of Regular building (RB)

Frequency has been sweeped from 0.05 Hz with an incremental of 0.05Hz and the resonance is recorded at 8.54Hz which is nearly about $\sqrt{30}$ times of resonant frequency of prototype. Figure 5 shows the variation of top storey displacement with excitation frequency. A maximum displacement of 10.44mm is observed at resonant frequency of 8.54Hz.

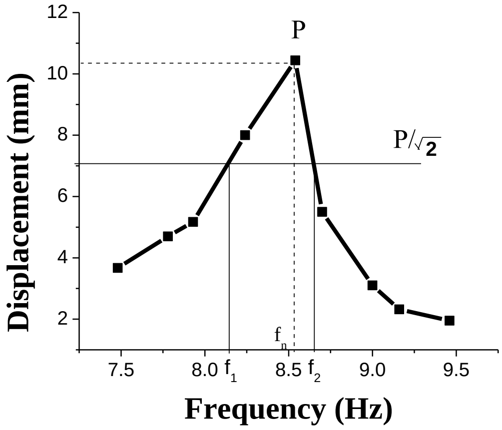


Figure 5. Top storey displacement versus frequency of regular scaled model (RB)

The damping ratio of the regular building is computed from "Half power band width" using Equation 1.

$$\xi = \left(\frac{f_2 - f_1}{2f_n}\right) \quad (1)$$

Where ξ is damping ratio, f_1 and f_2 are the frequencies corresponding to half power band width, f_n is the resonant frequency and 'P' is the peak displacement. Based on Equation 1 a value of 3.04% damping is obtained.

Harmonic excitation is generated by increasing the timestep to suit the resonance frequency of the prototype, using 0.121g acceleration recorded at the base of shaketable(base of model) at resonance. Figure 6 shows the harmonic loading of scaled model and prototype respectively and Figure 7 shows the corresponding fourier amplitude spectrum. From these figures it is clear that the harmonic motion generated have fundemental frequency of nearly $\sqrt{30}$.

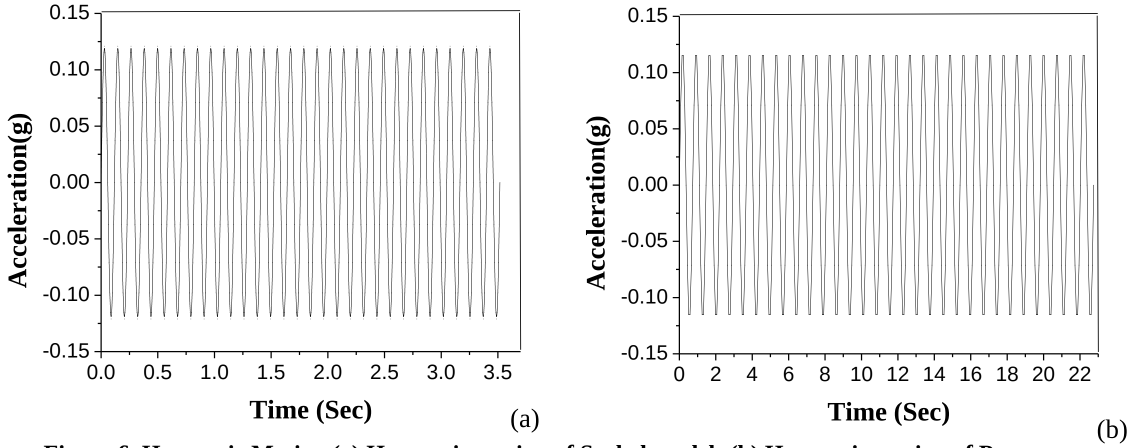


Figure 6. Harmonic Motion (a) Harmonic motion of Scaled model; (b) Harmonic motion of Prototype

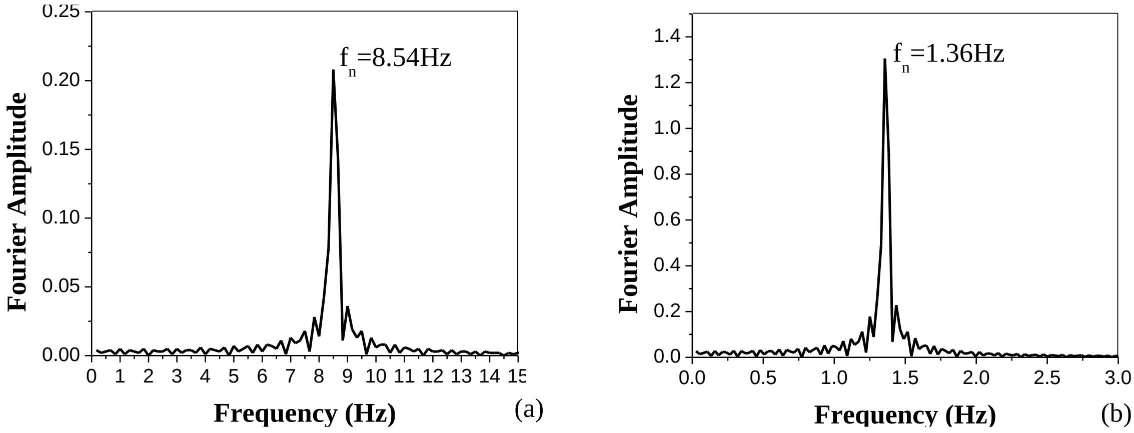


Figure 7. Fourier amplitude spectrum (a) Scaled model (8.54Hz); (b) Prototype (1.36Hz)

From Figure 6 it is observed that for 30 cycles with the same acceleration, time required for the prototype is 22 sec but for scaled model it is 3.5 sec i.e, time period is redused by $\sqrt{30}$.

This generated harmonic motion is provided as an input motion for evaluating the numerical model. Modelling and analysis have been carried out using Finite element method-based software SAP 2000 [29]. Storey displacements of both scaled model and prototype are presented in Table 8 and the same is as shown graphically in Figure 8. Hokmabadi et al. (2015) [20] have considered net displacement, which is obtained by deducting the shaketable displacement from the storey displacements, and the same procedure is implemented in the present work.

Table 8. Storey displacement (mm) of scaled model and prototype

Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	2.425	72.75	77.44
2	4.375	131.25	162.12
3	6.675	200.25	229.72
4	8.32	249.60	276.55
5	9.965	298.95	301.19

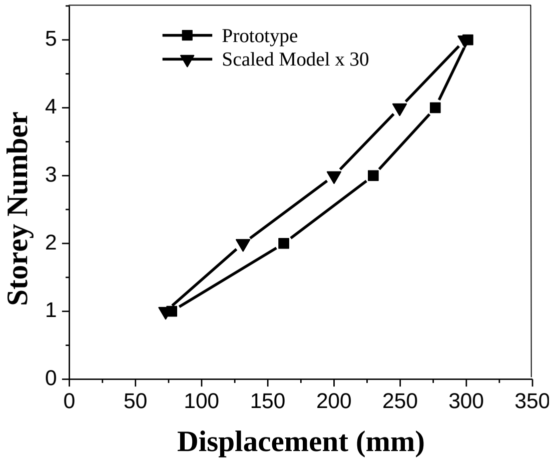


Figure 8. Variation of displacement with storey height

From Table 8 and Figure 8 it is observed that, both prototype and scaled model are in good correlation. The corresponding inter story drifts of the model and prototype structures are computed using Equation 2 and are illustrated in Figure 9. From Figure 9 it is clear that the storey drifts for the prototype structure are well within the acceptable limit as per the provisions.

$$D\ (i, i+1) = (d_{i+1} - d_i)/h \quad (2)$$

Where, $D_{(i,\ i+1)}$ is drift between the (i) and (i+1) levels; d_{i+1} is deflection at the (i+1) level; d_i is deflection at the (i) level and h= story height.

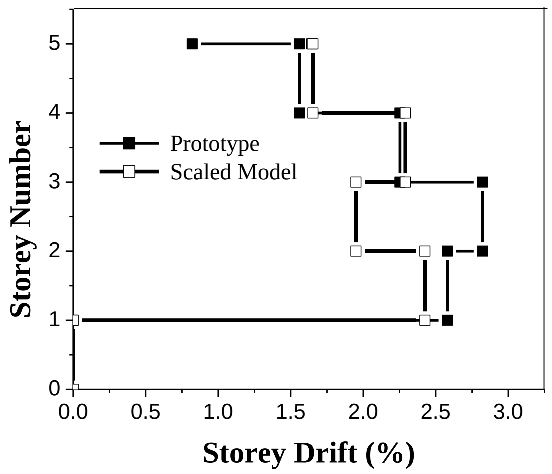


Figure 9. Variation of storey drift with number of storeys

4.1. Soil Structure Interaction

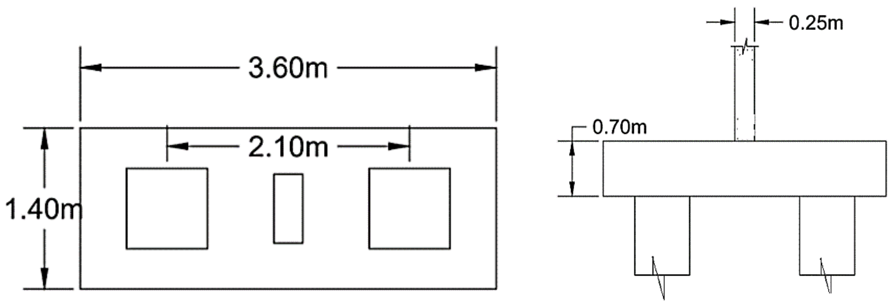
The structural response to seismic action is mainly dependent on, underlying soil, substructure and super structure. The effect on the soil motion by the interaction forces will depend upon the extent of the force and the flexibility of the soil foundation. However, if the soil beneath the structure is soft then SSI effect has to be included in the analysis as it amplifies the SSI effects.

Soil shear module is a combination of mass density and square of the shear wave velocity. Mass density in practice varies around 2000kg/m^3 in a comparatively narrow range, the main characteristics of soil stiffness is shear wave velocity (V_s). When 'V_s' is less than 300m/s then the soil is considered to be soft, hard when 'V_s' greater 800m/s and considered as rigid when 'Vs' is more than 1100m/s. In Rigid soil condition the SSI effects can be neglected [30]. Hence, in this present study soft clayey soil has been considered whose properties are given in Table 9.

Table 9. Properties of the soil

Sl. No.	Contents	Description
1	Young's modulus	25 MPa
2	Poisson's ratio	0.4
3	Density of soil	1470 kg/m^3.
4	Shear wave velocity	200 m/sec

Pile foundation is considered, seeing that the soil considered is soft. The pile foundation has been designed to be a pile group of 1×2 (Figure 10) for the highest load covering all columns from the structure (447.75 ≅ 450 kN). A square friction type pile foundation of M25 grade concrete has been designed. Details of the piles and pile cap are presented in Table 10. The safe load that can be carried by the pile is called its allowable load and it is obtained by dividing ultimate bearing capacity of the pile by factor of safety of 2.5.



(a) Plan **(b) Elevation**

Figure 10. Pile Cap

Table 10. Size of pile and pile cap

Sl. No.	Contents	Description
1	Pile size	700×70 mm
2	Pile length	9600 mm
3	Pile spacing	2100 mm
4	Pile cap size	1400×3600×700 mm

For experimental study both soil and pile foundation has been scaled which are as follows.

4.2. Scaling of Soil

Adopting the soil scaling mix suggested by Hokmabadi et al. (2015) [20], i.e. soil mix consisting of 60% Q38 kaolinite clay, 20% active bond 23 bentonite, 10% Class F fly ash, and lime each, with 100% water (percentage of the dry mix). The soil density on the second day was determined to be 1,470 kg/m^3.

4.3. Scaling of Pile

Adopting acrylic material, geometric and dimensional scaling has been adopted for scaling of pile and pile cap. The sizes of the pile group (scaled) are given in Table 11.

Table 11. Size of scaled pile and pile cap

Sl. No.	Contents	Description
1	Pile size	15×15 mm
2	Pile length	320 mm
3	Pile spacing	50 mm
4	Pile cap size	120×50×4.7 mm

Figure 11 depicts the view of scaled model (super structure and sub structure) along with prepared synthetic soil. Figure 12 demonstrates the dimensions of the experimental setup for SSI studies. Figure 13 displays the experimental setup of the SSI studies.

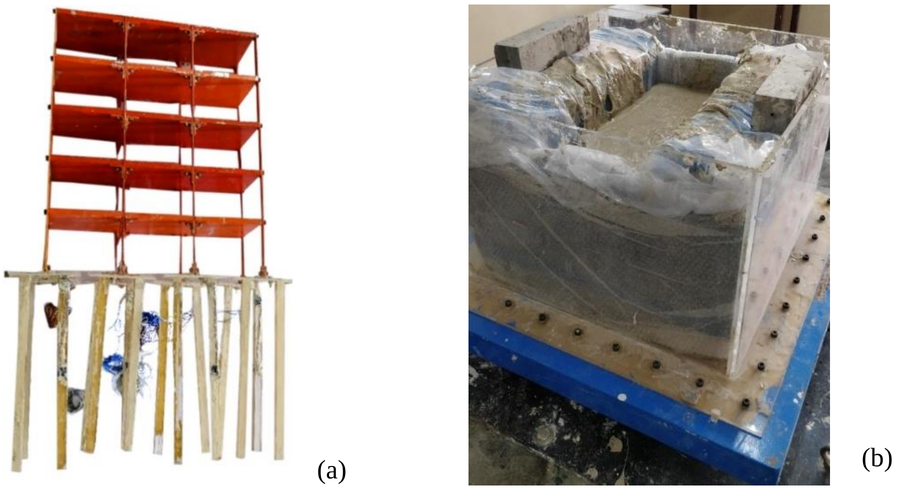


Figure 11. (a) Scaled superstructure and substructure; (b) Tank filled with prepared synthetic soil

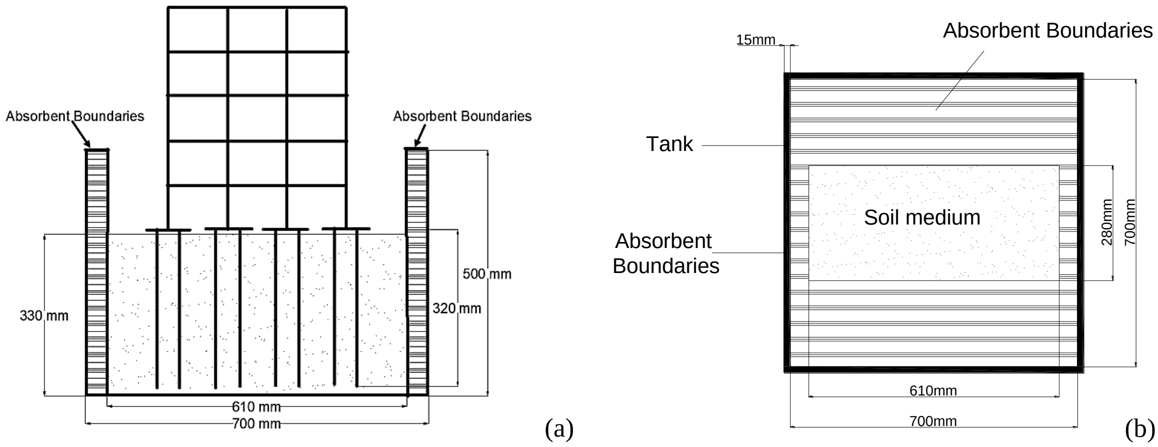


Figure 12. Soil – foundation - structure -model setup

Figure. 13. Experimental setup of the regular building

Frequency has been sweeped from 0.05 Hz with an incremental of 0.05Hz and the resonance is recorded at 7.02Hz. The variation of top storey displacement along with excitation frequency is presented in Figure 14. At resonant frequency (7.02Hz), a maximum displacement of 6.37 mm is observed at top storey and a base displacement of 0.51mm along with an acceleration of 0.0968g are recorded at the base of model (shaketable).

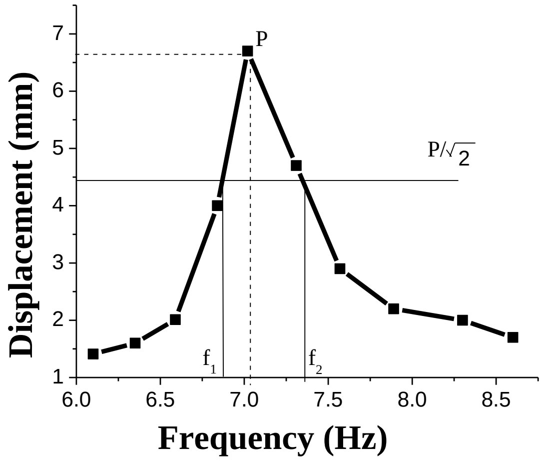
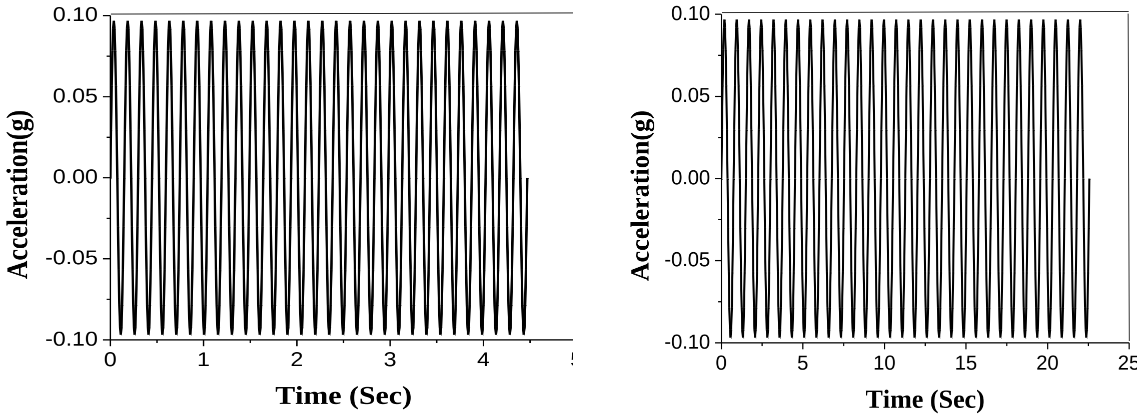


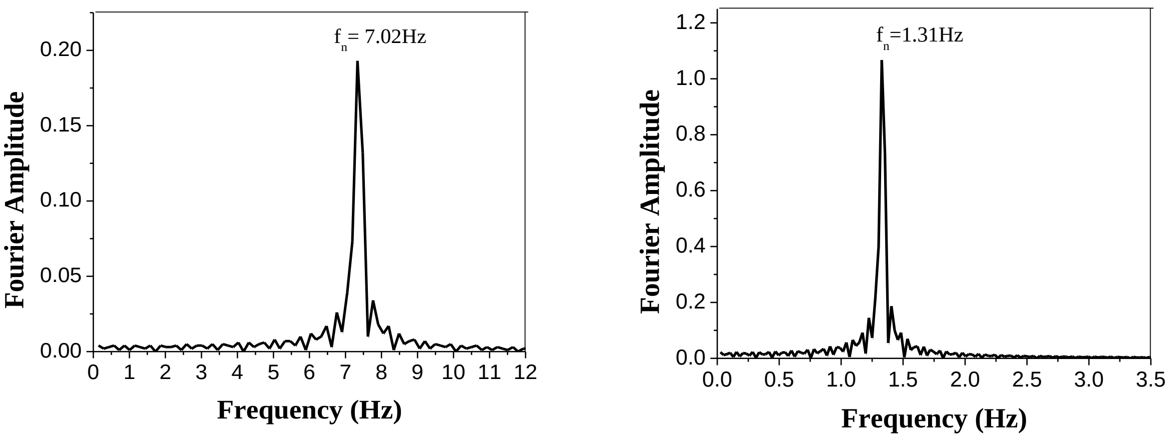
Figure 14. Variation of storey drift with number of storeys

The acceleration recorded at the base of shaketable (base of model) at resonance is adopted and the harmonic excitation is generated by increasing the timestep to suit the resonance frequency of the prototype as shown in Figure 15(b).This harmonic load was used for the analysis of the prototype. Figure 15 (a) shows the harmonic loading for model from the experiments and Figure 15(b) represent the generated harmonic motion for the prototype structure. Figure 16 indicates the fourier amplitude spectrum of the harmonic loads.



(a) Scaled model **(b) Prototype**

Figure 15. Harmonic Motion for (a) scaled model; (b) prototype



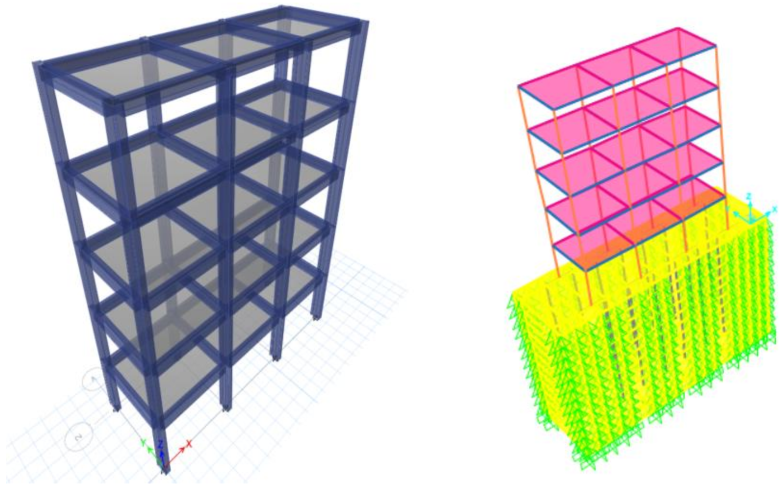
(a) Scaled model (7.02 Hz) **(b) Prototype (1.31 Hz)**

Figure 16. Fourier amplitude spectrum

From Figure 15 it is observed that for 30 cycles with the same acceleration, time required for the prototype is 22 sec but for scaled model it is 4.2 sec i.e, redused by $\sqrt{30}$. From Figure 16 it is noted that the resonant frequency of prototype also reduced nearly by $\sqrt{30}$ in comparision with scaled model.

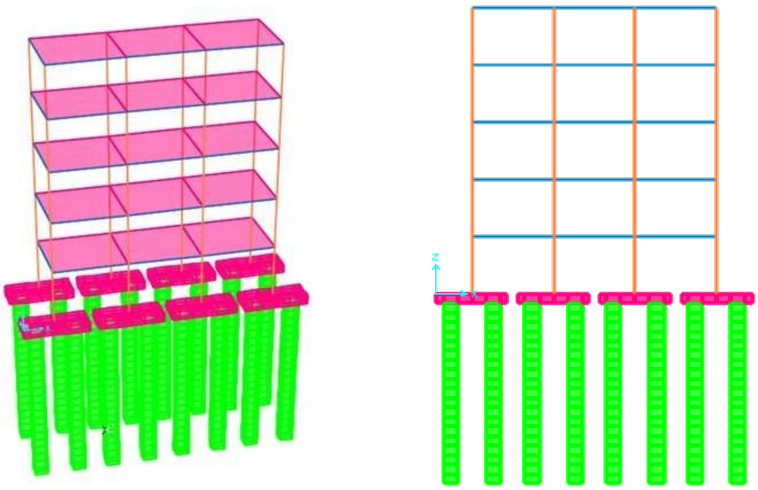
5. Numerical Study

A soil profile of width 280mm, length 610mm and height 350mm are considered for modelling which is exactly of dimensions used in the tank. Figure 17 depicts the three-dimensional view of a fixed base and flexible base numerical models and Figure 18 shows the three-dimensional view of pile and pile cap along with elevational view.



(a) (b)

Figure 17. Three-dimensional view of a (a) fixed base; (b) flexible base numerical models



(a) (b)

Figure 18. View of pile and pile cap (a) three dimensional; (b) elevational view

The generated harmonic motions are used as input motions for analysing numerical SSI model. Table 12 shows the displacement at different storey levels of experimental numerical model and the same is represented graphically as in Figure 19. Figure 19 indicates that storey displacements of SSI of scaled model and numerical prototypes are in good correlation.

Table 12. Storey displacement (mm) of scaled model and prototype

Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	2.10	63	50.00
2	3.70	111	104.57
3	5.42	162.6	151.04
4	6.00	180	185.04
5	6.50	198	204.00

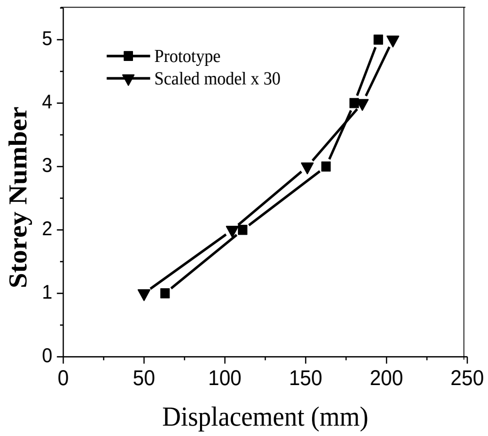


Figure 19. Variation of storey displacement with number of storeys

6. Comparative Study of Fixed Base and SSI Scaled Models

From experimental studies of fixed base (FB) and SSI scaled models, it is observed that the resonant frequency of the structure supported on soft soil is lesser than fixed base condition and also acceleration of the SSI model is lesser compared to fixed base model. Since these models are analysed for resonant condition, the generated harmonic load and the resonant acceleration is different. Hence in order to observe the behaviour these two models subjected to same harmonic loading, the generated harmonic motion of the structure considering soil structure interaction experimentally has been given to fixed base condition numerically. The storey displacements computed and presented in Table 13 and Figure 20 keeping their respective damping.

Table 13. Storey displacement (mm) of scaled models

Sl. No.	FB	SSI
1	0.936	2.1
2	1.77	3.7
3	2.46	5.42
4	2.94	6
5	3.19	6.6

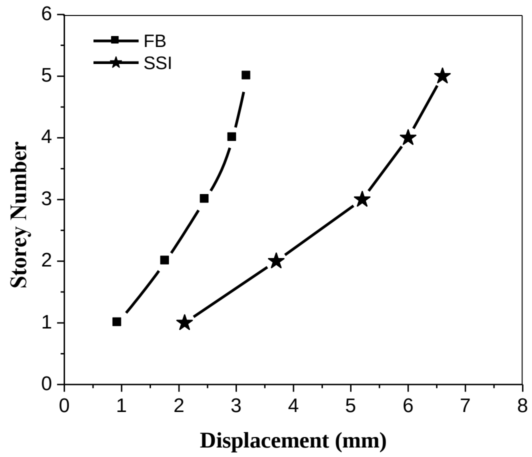


Figure 20. Variation of storey displacement with number of storeys

From Figure 20 it is seen that storey displacements of SSI model is comparatively higher than fixed base model.

7. Experimental and Numerical Studies on Setback Buildings

The procedure used for analysis of regular building model (Type-RB) is implemented for other setback models (Type SB1 to SB4). Mass by volume ratios of all the setback models SB1 to SB4 are presented in Table 14. Figure 21 shows scaled setback models and numerical prototypes.

Table 14. Mass by volume ratios of all the models

Description	Type SB1	Type SB2	Type SB3	Type SB4
Scaled Model	381.67 kg/m^3	335.26 kg/m^3	335.42 kg/m^3	386.19 kg/m^3
Prototype	342.48 kg/m^3	343.33 kg/m^3	350.13 kg/m^3	350.13 kg/m^3

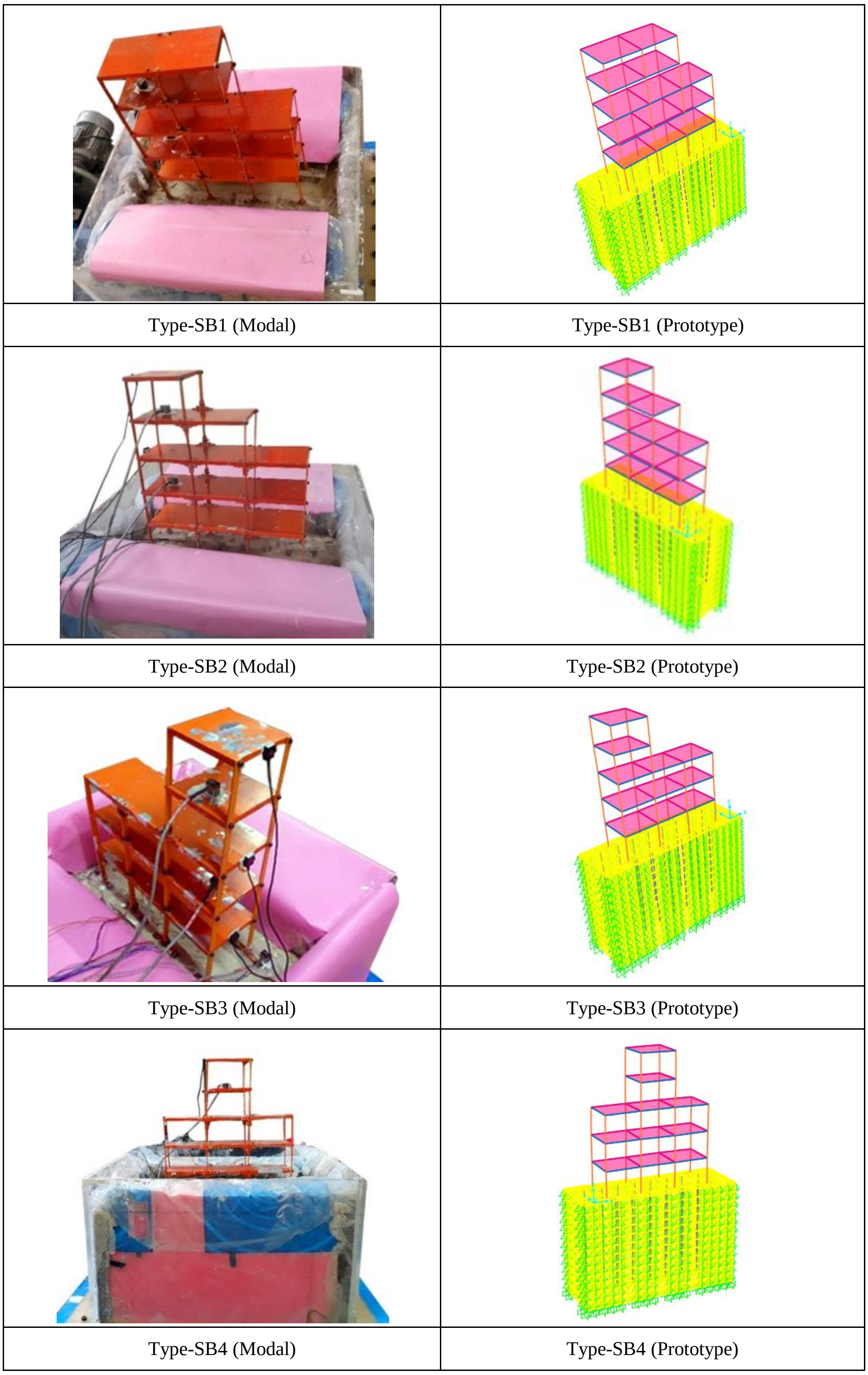


Figure 21. Scaled experimental models and numerical prototypes of setback buildings (SSI)

Frequency of vibration has been swept with an increment of 0.05Hz and the resonance of the scaled setback models are recorded and presented in Table 15. Acceleration and displacement (mm) at the base of models are presented in Table 16.

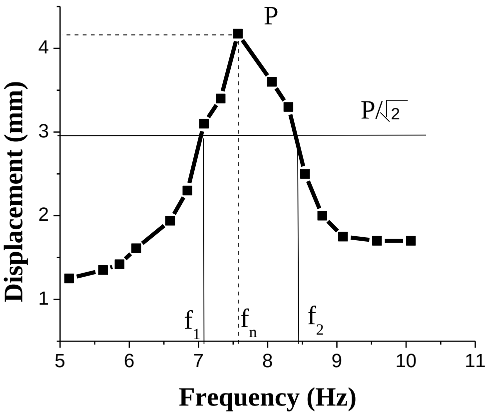
Table 15. Resonant Frequencies of the flexible base setback models in Hz

Description	Numerical study (Prototype)	Experimental study (Scaled model)
SB1	1.42	7.57
SB2	1.54	8.12
SB3	1.67	8.42
SB4	1.62	8.18

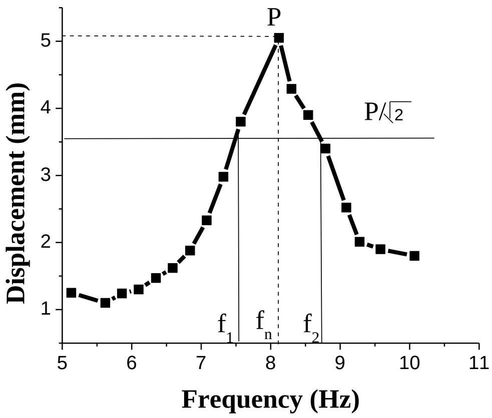
Table 16. Recorded Acceleration and Displacement at the base of tank

Description	Acceleration (g)	Base Displacement
RB	0.0968	0.51
SB1	0.119	0.575
SB2	0.123	0.579
SB3	0.169	0.685
SB4	0.17	0.685

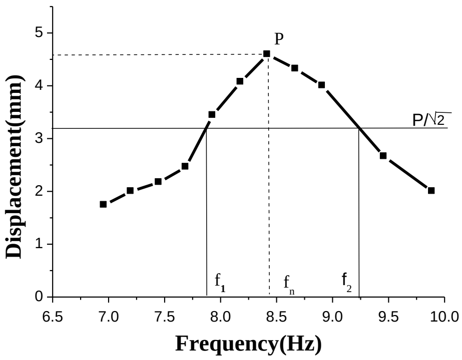
Structural damping has been computed for these scaled setback models by Half power band width using equation 1 and the results are presented in Figure 22 and Table 17.



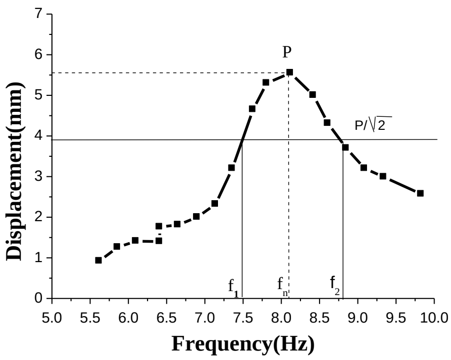
Type -SB1



Type -SB1



Type -SB1



Type -SB1

Figure 22. Damping of Setback scaled models

Table 17. Structural damping of the setback models

Description	Damping (%)
SB1	8.8
SB2	6.8
SB3	8.9
SB4	7.6

Adopting the acceleration from Table16 and damping values from Table 17, the prototypes were analysed numerically. Tables 18 to 21 shows the storey displacement comparison of experimental and numerical models of Type SB1 to SB4 buildings respectively. Figure 23 shows the comparison of storey wise displacements for all buildings for both prototype and scaled models, Figure 24 shows the storey drifts of the scaled models and prototype.

Table 18. Storey displacement (mm) of scaled model and prototype of Type SB1 building

Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	0.71	21.30	27.61
2	1.89	56.70	56.86
3	2.6	78.00	80.59
4	3.1	93.00	100.24
5	3.6	108.00	111.71

Table 19. Storey displacement (mm) of scaled model and prototype of Type SB2 building

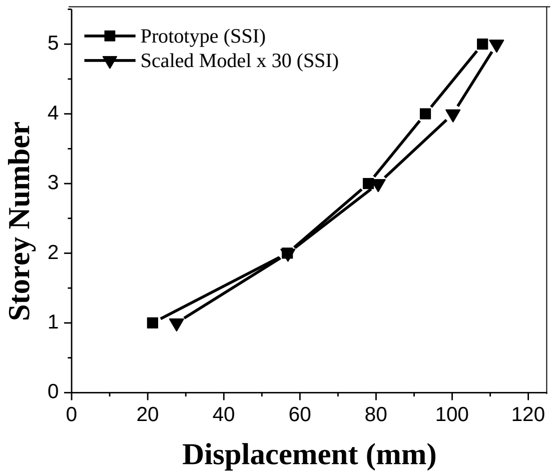
Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	1.12	57	31.27
2	2.3	69.00	64.48
3	3.13	93.9	90.29
4	3.95	118.5	109.77
5	4.64	139.2	122.19

Table 20. Storey displacement (mm) of scaled model and prototype of Type SB3 building

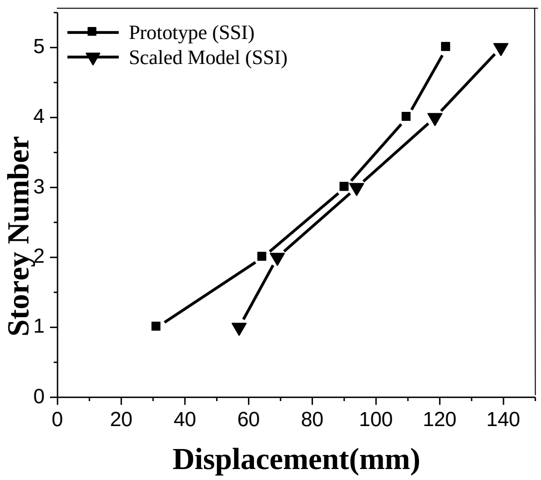
Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	1.3	39	32.88
2	1.91	57.3	67.11
3	2.67	80	93.26
4	3.2	96	121.14
5	3.97	119.1	139.11

Table 21. Storey displacement (mm) of scaled model and prototype of Type SB4 building

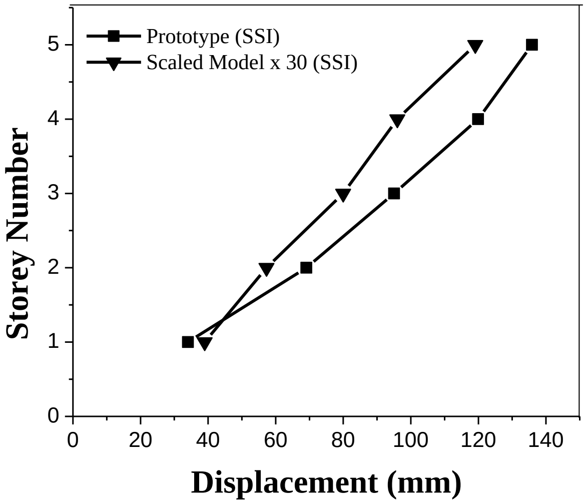
Storey No's	Displacement of Scaled Model (Δ)	Displacement of Prototype Building (Δx30)	Displacement of Prototype Building (Numerical Analysis)
1	1.07	32.1	34.040
2	2.15	64.5	69.10
3	3.43	102.9	95.05
4	4.33	129.9	119.90
5	4.88	146.4	135.85



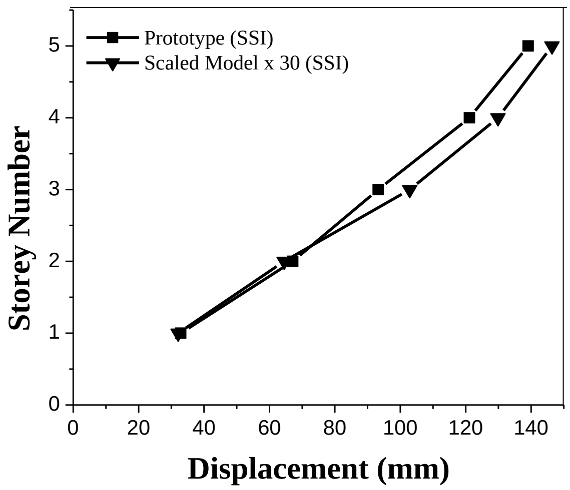
Type-SB1



Type-SB2

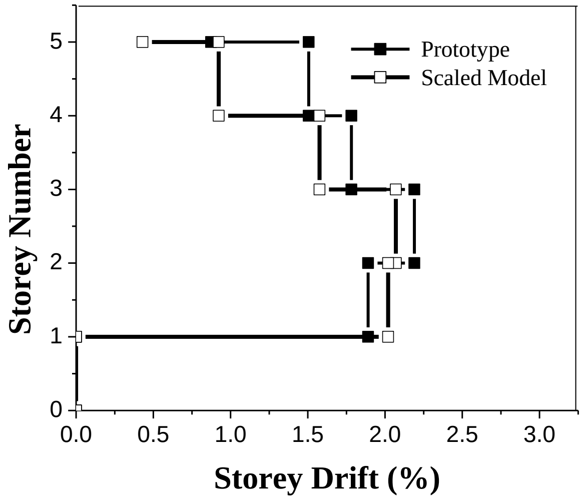


Type-SB3

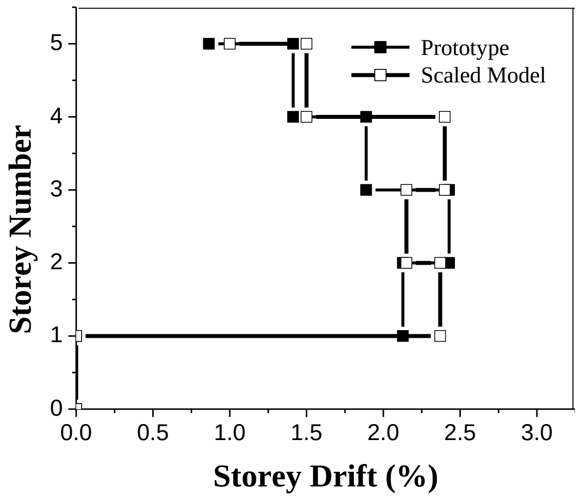


Type-SB4

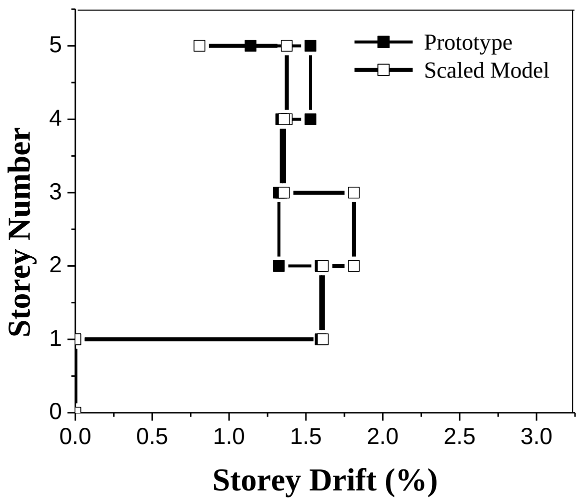
Figure 23. Displacements comparison of prototype and scaled setback models



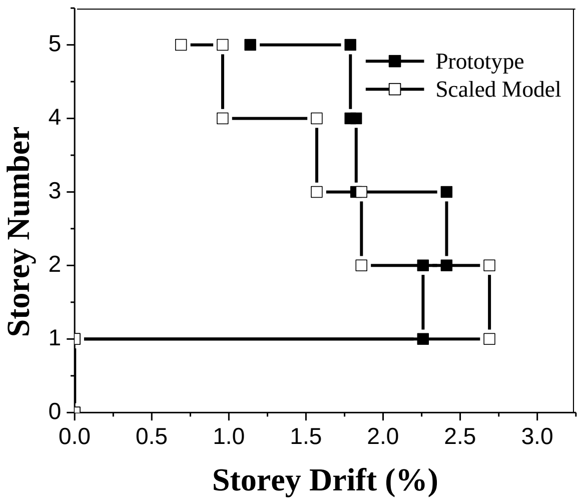
(a) SB1



(b) SB2



(c) SB3



(d) SB4

Figure 24. Variation of storey drift with number of storeys

From Figures 23 and 24 it is seen that the displacements and storey drifts of both scaled models and prototypes of SB1 to SB4 for sinusoidal ground motion are almost same.

8. Conclusion

The irregularity indices of the selected buildings indicate wide range of values with different codal provisions. From the computation of the irregularity indices, it is found that setback buildings SB3 and SB4 are having identical irregularity indices as per Eurocode (2004) and ASCE (2005) but different as per IS: 1893-2016. Therefore, there is a need for further studies to develop generalised procedures to compute irregularity indices. As no experimental investigations have been carried out previously to understand the seismic response of the setback buildings with SSI effects, an attempt has been to evaluate the behaviour of these buildings under seismic excitations by conducting experiments on scaled models and the results are compared with numerical analysis. Based on the results from both experimental and numerical studies on these setback buildings, it is observed that resonant frequency and storey displacement of buildings resting on soft soils is found to increase with the increasing in irregularity indices. It is also seen that, both asymmetrical (SB3) and symmetrical (SB4) setback buildings exhibited nearly same amount of storey displacements and resonant frequency. Further, in comparison with the setback buildings, regular building displayed larger amount of storey displacements. However, detailed parametric studies including the effect of number of bays and storeys are required to understand the seismic behaviour of these setback buildings.

9. Declarations

9.1. Author Contributions

R.M.T., L.G. and V.D. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in article.

9.3. Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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