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ORIGINAL CONTRIBUTION

Seismic Response of Steel Braced Building Frame Considering Soil Structure Interaction (SSI): An Experimental Study

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Abstract Conventional fixed-base analysis ignoring the effect of soil-flexibility may result in unsafe design. Therefore, to evaluate the realistic behavior of structure the soil structure interaction (SSI) effect shall be incorporated in the analysis. In seismic analysis, provision of bracing system is one of the important option for the structure to have sufficient strength with adequate stiffness to resist lateral forces. The different configuration of these bracing systems alters the response of buildings, and therefore, it is important to evaluate the most effective bracing systems in view point of stability against SSI effect. In present study, three RC building frames, G+3, G+5 and G+7 and their respective scaled down steel model with two types of steel bracing system incorporating the effect of soil flexibility is considered for experimental and analytical study. The analytical study is carried out using Elastic continuum approach and the experimental study is carried out using Shake Table. The influence of SSI on various seismic parameters is presented. The study reveals that, steel bracing system is beneficial to control SSI effect and it is observed that V bracing is more effective, in resisting seismic load considering SSI.

Keywords Steel bracing system ·
Soil structure interaction · Elastic continuum approach ·
Shake table · Natural frequency

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Introduction

In reality, response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil which is known as Soil-Structure Interaction (SSI). Traditionally, it has been considered that SSI can be conveniently neglected for conservative design. In addition, neglecting SSI tremendously reduces the complication in the analysis of the structures which has tempted designers to neglect the effect of SSI in the analysis. Unfortunately, the assumption does not always hold true. In fact, the SSI can have a detrimental effect on the structural response, and neglecting SSI in the analysis may lead to unsafe design for both the superstructure and the foundation. Therefore, consideration of SSI effects in seismic design of concrete moment resisting building frames is essential [1–3].

For tall buildings, the gravity load resisting system cannot resist lateral forces efficiently. It is well recognized that the incorporation of lateral force resisting systems in the form of shear walls, bracing systems etc. improve the structural performance of building subjected to lateral forces due to earthquake excitation. The studies have been carried to minimize the SSI effect by incorporating stiffness to the structure by many possible provisions such as shear wall, strap beam and bracing system [4–7]. Bracing systems are used to resist horizontal forces (wind load, seismic action) and to transmit it, to the foundation. Such system reduces bending moment and shear force in the columns. There are different types of bracing systems in common use such as diagonal bracing, X bracing, V bracing.

Conventionally two basic classical approaches, viz., Winkler approach and Elastic Continuum approach (ECM) are used to study SSI [8, 9]. ECM is an approach of

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physical representation of the infinite soil media. Soil mass basically constitutes of discrete particles compacted by some inter-granular forces. In the ECM idealization, generally soil is assumed to be semi-infinite and isotropic for the sake of simplicity. However, the effect of soil layering and anisotropy may be conveniently accounted for in the analysis. This approach provides much more information on the stresses and deformations within soil mass than Winkler model [8]. It has also the important advantage of simplicity of the input parameters, viz., modulus of elasticity and Poisson's ratio. Therefore, it is observed that ECM is an effective approach for consideration of soil mass beneath foundation [2].

In the present study an attempt is made to identify the effect of SSI on the seismic performance of structure and thereafter to study effectiveness of alternate bracing system in order to control SSI effect by carrying out experimental study and comparing them with analytical results for the validation.

Objective

The objective of the present study is to investigate the SSI effect on the dynamic properties of bare frame and frames with steel bracing (composite building frame) such as Natural Frequency and Time Period resting on soft soil. The results are obtained by experimental and analytical study. Experimental study is carried out on scaled down steel model using Shake Table and analytical study is carried out by structural analysis software SAP 2000 [10]. Following are the objectives of proposed study.

1. To study the Soil structure interaction (SSI) effect on building frame.

2. To evaluate the effectiveness of bracing in the structure to reduce the SSI effect.
3. To identify the best possible type of bracing to improve the performance of building.
4. To access and verify the effectiveness of experimental study with reference to analytical study in order to evaluate SSI effect.

Prototype RC Building Frame Considered for the Analysis

In the present work, three RC building frames are considered which are analyzed and designed as per codal provision [11, 12]. The structures considered are square in plan with single bay in both directions. Dimensional characteristics are illustrated in Table 1.

Preparation of Scaled-Down Structural Model

The critical part for experimental study was to develop an experimental model able to represent with the less degree of distortion. One fundamental issue to be considered at this stage is the fact that the construction of a 'true replica' model that satisfies all the similitude requirements needed by dimensional analysis is almost an impossible task due to material limitations. The main limitations for the present study were the use of materials and the pay load capacity of the Shake Table (30 kN). The major task in the scaling down process is to achieve "Dynamic Similarity" where model and prototype experience homologous forces [13]. According to this approach two principal test conditions are established.

Table 1 Geometric and material properties of building frames

sr. no	Contents	Description		
1	Structure	OMRF	OMRF	OMRF
2	No. of stories	G+3	G+5	G+7
3	Storey height	3.5 m	3.5 m	3.5 m
4	Grade of concrete	M 25	M 25	M 25
5	Grade of steel	Fe415	Fe415	Fe415
6	Bay width (both direction)	4 m	4 m	4 m
7	Slab thickness	0.15 m	0.15 m	0.15 m
8	Size of column	0.45 m × 0.3 m	0.40 m × 0.25 m (top three storey)	0.45 m × 0.3 m (top four storey)
			0.45 m × 0.45 m (bottom three storey)	0.55 m × 0.50 m (bottom four storey)
9	Size of beam	0.4 m × 0.23 m	0.4 m × 0.23 m	0.4 m × 0.23 m
10	Floor finish	0.6 kN/m^2	0.6 kN/m^2	0.6 kN/m^2
11	Live load	4 kN/m^2	4 kN/m^2	4 kN/m^2
12	Seismic zone	III	III	III

1. Natural frequency of the prototype should be scaled by an appropriate scaling relation to that of model.
2. Density of the prototype and model should be similar.

Scale Factor

Adopting appropriate geometric scale factor is one of the important steps in scale modeling on Shake Table. Due to size limitation of Shake Table, the C/C distance between two columns is set as 0.32 m leading to a linear scale factor, of $4.0/0.32 = 12.5$ (column spacing in prototype structure is 4 m).Therefore, Employing geometric scaling factor of 1:12.5 as explained above height, length, and width of the structural model are obtained as 1.120, 0.32 and 0.32 m, respectively. The scaling relations for the various parameter adopted in this study, are shown in Table 2 [13–15].

Typical scaling down procedure for G+3 building model is describe below.

According to the first principle, the relation between natural frequency of model and prototype is

$$\begin{aligned} f_m/\ f_p &= S^{-1/2} \\ &= 3.54 \end{aligned} \tag{1}$$

Natural frequency of the G+3 prototype structure as calculated by application software (modal analysis) is, $f_p = 1.4792$ Hz. Therefore required frequency of the model (f_m) is 5.24 Hz.

Also, according to second principle density of the prototype structure (ρ_p) is work out and it is 264.01 kg/m^3.

Therefore the mass of the structural model (M_m) is estimated as:

$$\begin{aligned} M_m &= \rho_m \times\ V_m \\ &= 264.01\ \times (1.12 \times 0.32 \times 0.32) \\ &= 30.27\ Kg \end{aligned}$$

The dimensions of column and slab of scaled down steel model is determined so that the weight of model nearly equals to 30.27 kg as required by simulated laws. Considering all above the details of G+3 scaled down steel model is worked out. Similar calculations were done for G+5 and G+7 steel models and the details are presented in Table 3.

A typical G+3 scaled down steel model details are given in Fig. 1.

## Experimental Study using Shake Table

The Shake Table at the Civil Engineering Department, Walchand Institute of Technology, Solapur, is uniaxially driven having table size 2 m $\times$ 2 m with maximum payload capacity of 30 kN. The table has an operating frequency range of 0.01–50 Hz.

In the present study objective is to evaluate the change in the dynamic properties of structure such as Natural frequency and Time period for fixed base and flexible base condition (SSI). Therefore experimental set ups are developed in the laboratory to produce fixed base condition and flexible base condition. These are described below:

Table 2 Scaling relations in terms of geometric scaling factor (S) [13]

Parameters	Scale factor
Mass density	1
Stiffness	S^2
Force	S^3
Modulus	S
Acceleration	1
Frequency	$S^{-1/2}$
Time	$S^{1/2}$
Shear wave velocity	$S^{1/2}$
Length	S
Stress	S
Strain	1
EI	S^5

Table 3 Geometric and material properties of steel scaled down model

Sr. no	Contents	Description		
1	No. of stories	G+3	G+5	G+7
2	Storey height	280 mm	280 mm	280 mm
3	Grade of steel	Fe250	Fe250	Fe250
4	Bay width	320 mm	320 mm	320 mm
5	Slab thickness	4 mm	3 mm	3 mm
6	Size of column	10 mm $\times$ 10 mm	12 mm $\times$ 12 mm	12 mm $\times$ 12 mm
7	Size of plinth beam	10 mm $\times$ 10 mm	12 mm $\times$ 12 mm	12 mm $\times$ 12 mm

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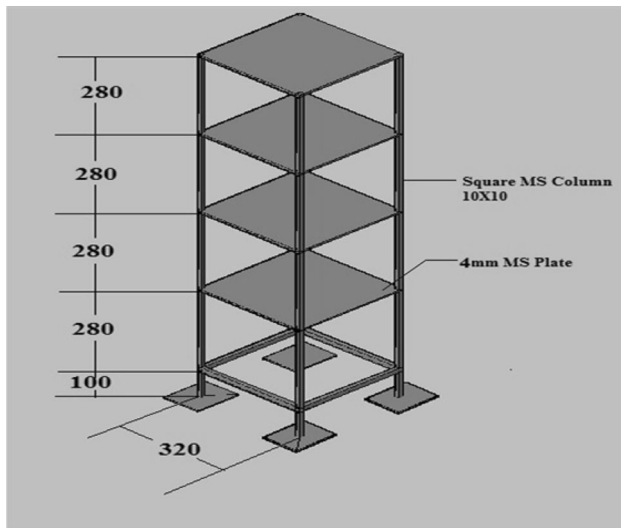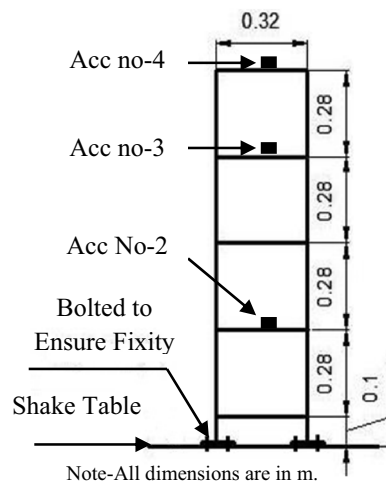

Fig. 1 Typical view of G+3 steel scaled down model

Fixed Base Condition

The fixed-base response of the scaled down model is investigated by securing the foundation directly to the platform of the shaking table. There are 4 numbers of accelerometers used to acquire the data. Accelerometer no. 1 is at bottom of Shake Table (Actuator), no. 2 and 3 are at slab level and accelerometer no. 4 is at roof level of scaled down model. The placements of accelerometers are shown in Fig. 2.

Flexible Base Condition

Flexible base conditions refer to the case wherein the foundation along with the sub soil is considered. To simulate this condition in the laboratory a confined soil mass beneath the footing is required to be used. Therefore a container made of steel plates is used to produce this confinement as shown in Fig. 3. The experimental Scaled-

Down model is square in plan. Therefore in order to have equal quantity of soil all around the model on all sides, the square container is used. The plan dimensions of this container is kept to the maximum possible extent considering the size limitation of Shake Table (2 m × 2 m) and adequate space required for the fixtures for mounting the container on Shake Table.

The depth of the container is decided based on the requirement to account for embedment depth [16]. Payload capacity (30 kN) of Shake Table is also took into consideration while developing the set up. Thus in view of all these, the steel container of size 1.5 m × 1.5 m × 0.7 m is used. The soil is filled in and compacted in layers of 10 cm thickness with 95% of MDD. After the completion of filling, the experimental model is kept on the soil mass. The complete set up for the flexible base condition is shown in the Fig. 3. The various properties of soil used for the study is determined in the laboratory [17–21]. These are presented in Table 4.

Effectiveness of Bracing

Two types of bracings, i.e. diagonal and V type are considered in order to evaluate their effect to control SSI. The bracing effect is studied with flexible base condition. The typical arrangement of V braced system is shown in Fig. 4.

Results and Discussion-Scaled Down Steel Model

In order to get natural frequency of steel model, the model was subjected to a gradually increasing unidirectional harmonic excitation (sine sweep wave) with amplitude in the range of 0.4–0.7 mm and sweep rate in the range of 0.05–0.14 Hz/s. The results are obtained for fixed and flexible base condition which is discussed below.

Fig. 2 Experimental set up for fixed base condition

Note-All dimensions are in m.
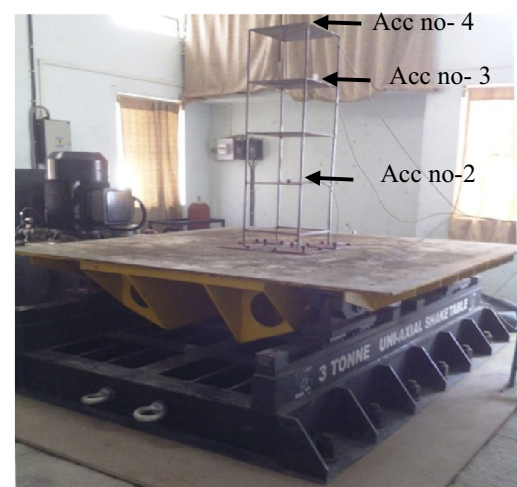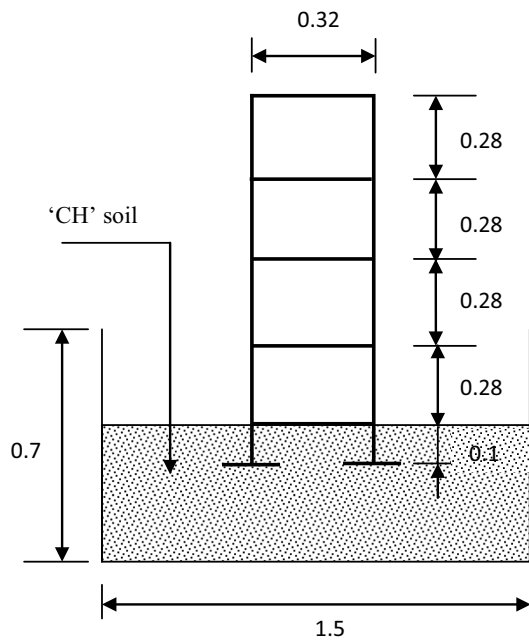
Note – All dimensions are in m

Fig. 3 Experimental set up for flexible base condition

Table 4 Properties of soil used in the study

Sr. no.	Name of test	Soil property
1	Specific gravity	2.63
2	Compaction properties	
	Maximum dry density (kN/m^3)	13.8
	Optimum moisture content (%)	27
3	Strength parameters	
	Soil internal frictional angle (Ø) in °	2
	Cohesion 'C' (kN/m^2)	63.34
4	Atterberg's consistency limits	
	Liquid limit (%)	58.9
	Plastic limit (%)	38.88
	Shrinkage limit (%)	5.45
5	Particle size distribution analysis	
	% of gravel	–
	% of sand	11
	% of silt	18
	% of clay	71
	Coefficient of uniformity (Cu)	–
	Coefficient of curvature (Cc)	–
6	Unit weight (kN/m^3)	14.4
7	Classification of soil	CH (Highly compressible clay)
8	Modulus of elasticity 'E' (kN/m^2)	13,070
9	Poisson's ratio 'μ'	0.4

Fixed Case

The Frequency Response Function (FRF) and Fast Fourier Transformation (FFT) plots for fixed base condition of various building models are obtained for all the accelerometers. The typical FRF and FFT plot of G+3 steel scaled down model are shown in Fig. 5. In this figure, blue line indicates the response of accelerometer no. 4, red line of accelerometer 3 and green line of accelerometer no.2. The peak of FRF and FFT is considered as natural frequency.

From FRF and FFT plots (Fig. 5) of G+3 building model, it is observed that, the natural frequencies are 7.5 and 7.2 Hz respectively. Thus the average value of 7.25 Hz is taken as natural frequency for fixed base condition.
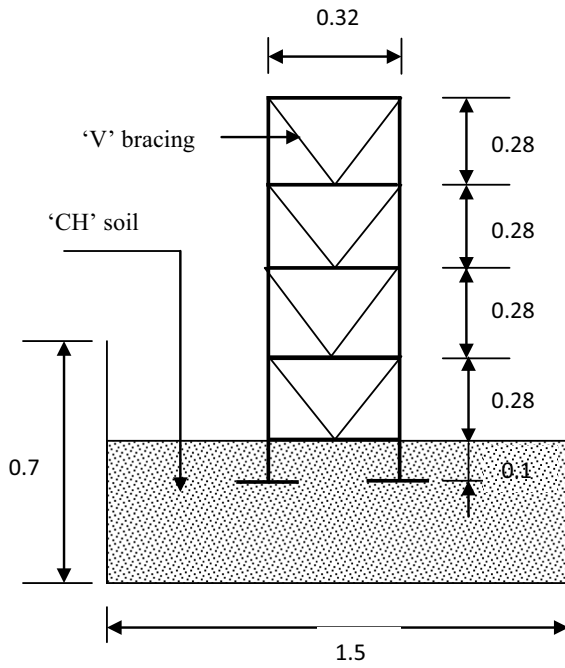
Flexible Case

Flexible base condition is studied for three cases that is bare frame, frame with diagonal bracing and frame with bracing. These are discussed in detail below.

A. Bare Frame

The typical FRF and FFT plot of G+3 model for flexible base condition is shown in Fig. 6.

From FFT and FRF plots (Fig. 6), it is observed that, the natural frequency is 5.1 and 5.5 Hz respectively. Thus the average value of 5.3 Hz is taken as natural frequency for bare frame condition.

Note – All dimensions are in m

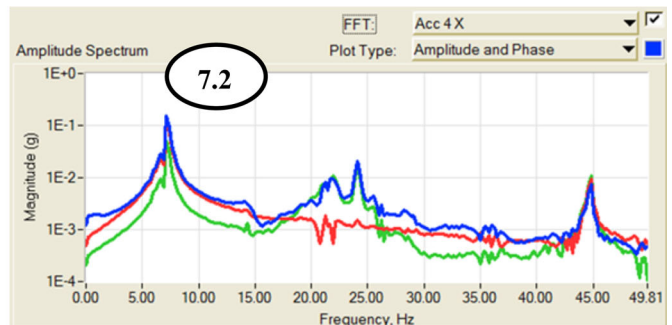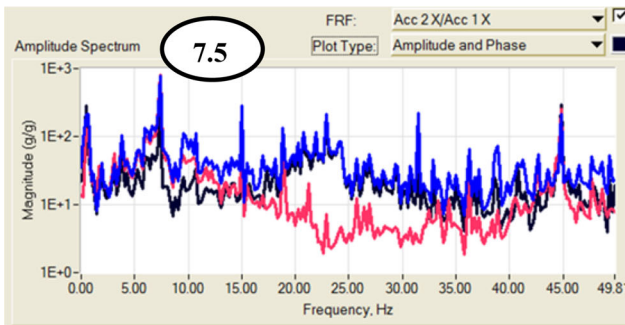**Fig. 4** Experimental set up for flexible base condition with V bracing

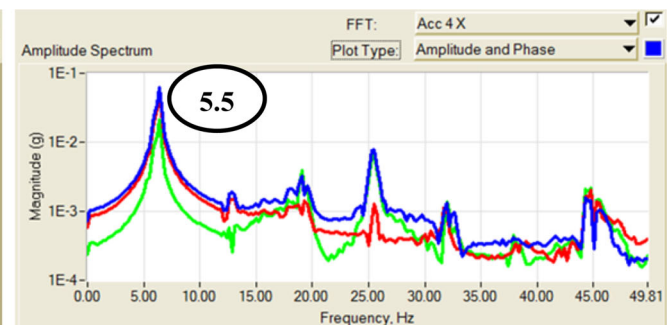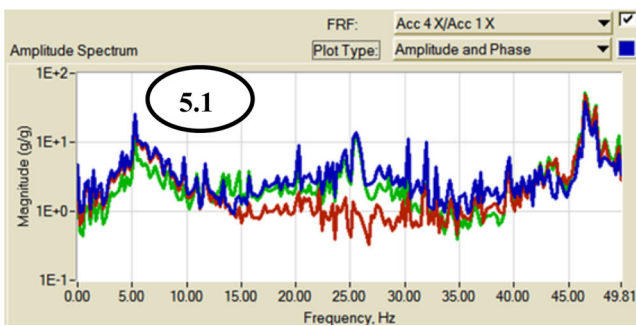**Fig. 5** Combined FRF and FFT for G+3 steel scaled down model-fixed case

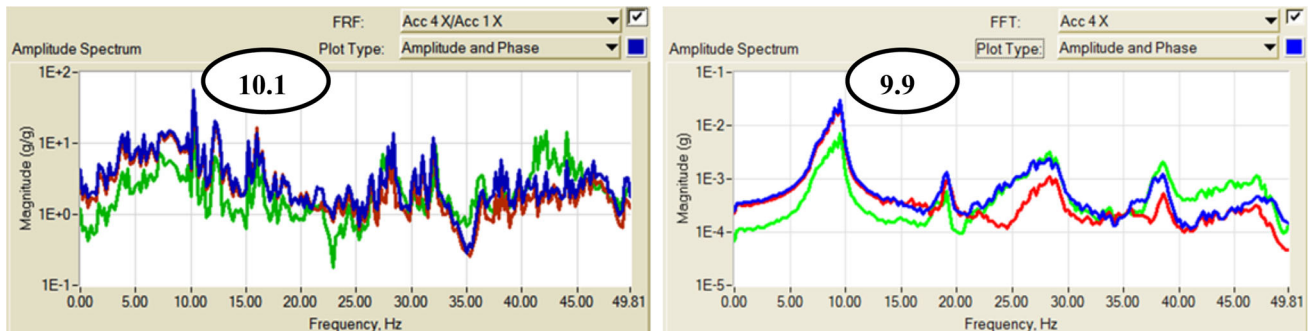**Fig. 6** Combined FRF and FFT for G+3 steel scaled down model-bare frame

Fig. 7 Combined FRF and FFT for G+3 steel scaled down model-diagonal bracing
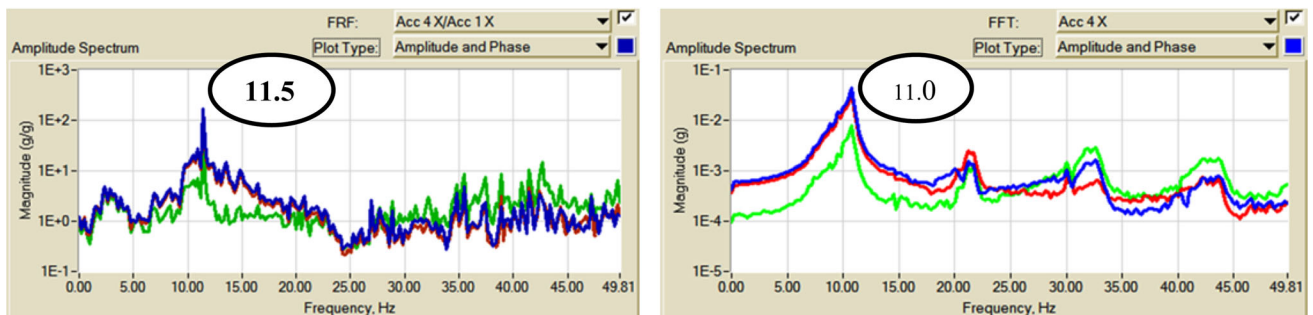

Fig. 8 Combined FRF and FFT for G+3 steel scaled down model-V bracing

Table 5 Results obtain using shake table for steel scaled down model

Scaled down model	Case	Designation	Notation	Natural frequency (Hz)	Time period (S)
G+3	1	Fixed base	FB	7.25	0.1379
	2	Flexible base with bare frame	(FL)BF	5.3	0.1886
	3	Flexible base with diagonal bracing	(FL)DB	10	0.1
	4	Flexible base with V bracing	(FL)VB	11.25	0.0889
G+5	1	Fixed base	FB	4.9	0.204
	2	Flexible base with bare frame	(FL)BF	4.45	0.2247
	3	Flexible base with diagonal bracing	(FL)DB	7.55	0.1324
	4	Flexible base with V bracing	(FL)VB	8.1	0.1234
G+7	1	Fixed base	FB	3.15	0.3174
	2	Flexible base with bare frame	(FL)BF	2.75	0.3636
	3	Flexible base with diagonal bracing	(FL)DB	4.45	0.2247
	4	Flexible base with V bracing	(FL)VB	4.95	0.2020

B. Frame with Diagonal Bracing

The typical FRF and FFT plot of G+3 model for flexible base condition with diagonal bracing is shown in Fig. 7.

From FRF and FFT plots (Fig. 7), it is observed that, the natural frequencies are 10.1 and 9.9 Hz respectively. Thus the average value of 10.0 Hz is taken as natural frequency for diagonal bracing condition.

C. Frame with V Bracing

The typical FRF and FFT plot of G+3 model for flexible base condition with V bracing is shown in Fig. 8.

From FRF and FFT plots (Fig. 8), it is observed that, the natural frequencies are 11.50 and 11.0 Hz respectively. Thus the average value of 11.25 Hz is taken as natural frequency for V bracing condition.

Fig. 9 Typical G+3 steel
scaled down model develop
using SAP 2000. **a** Fixed base
condition, **b** flexible base
condition

(a)   (b)
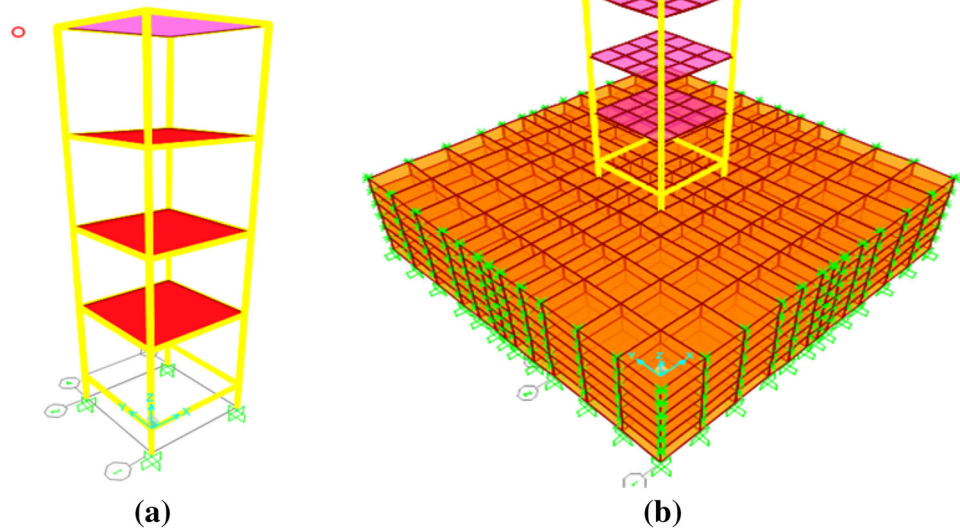
Similarly FRF and FFT plot of G+5 and G+7 building
model are obtained using Shake Table for all the cases and
results are summarized in Table 5.

Comparison of Result by Analytical Study

Analytical study is carried out using SAP 2000 software
[10]. The laboratory set up is simulated using SAP 2000.
Soil mass foundation and building frame is developed by
Finite Element Method (FEM). The beams and columns are
modeled as frame element. The soil is assumed to be linear,
elastic and isotropic material. The foundation and soil is
discretized as eight-nodded brick element.

In SAP 2000 models are generated for fixed and flexible
base condition and also for different bracing system. Fig-
ure 9 shows typical G+3 model generated in SAP 2000 for
fixed and flexible case. The natural time period and fre-
quency of G+3, G+5 and G+7 building model are
obtained by modal analysis using SAP 2000. These are
presented in Table 6.

The comparison of time period obtained by experi-
mental and analytical study on scaled down steel model is
shown in Fig. 10.

It is observed from Fig. 10 that due to incorporation of
support flexibility, the time period increases by almost 37%
for bare frame ((FL)BF). However due to incorporation of
bracing, time period reduces by almost 46% for diagonal
bracing system ((FL)DB) and 52% in case of V bracing
system ((FL)VB). This revels that provision of bracing
reduces the time period and helps to control the SSI effect.
From the study, it is observed that V bracing are more
effective as it produces minimum time period.

From Fig. 10 it is also observed that for G+3 building
frame the time period obtained experimentally is higher
than analytical study. For fixed base condition time period
obtain experimentally are almost 11% higher than analyt-
ical study. For flexible base also same trend is observed.
For bare frame, diagonal braced frame and V braced frame
time period by experimental study is 14, 20, and 21%
higher than analytical study respectively. The above all
observation indicates that for all the cases experimental
study yield almost 14–21% higher time period than ana-
lytical study. Almost same trend is observed for G+5 and
G+ 7 steel scaled down model.

Results and Discussion-Prototype Structure

In order to simulate the frequency of steel scaled down
model with prototype structure, the results of steel scaled
down model are converted using equation no 1 as per
similitude law. The converted experimental results are then
compared with analytical results of prototype structure
obtained by SAP 2000 software. The results are given in
Table 7.

The comparison of time period obtained by experi-
mental and analytical study of prototype structure is shown
in Fig. 11.

It is observed from Fig. 11 that due to incorporation of
support flexibility the time period increases ((FL)BF) by
almost 18% for bare frame. However due to incorporation
of bracing time period reduces by almost 37% for diagonal
bracing system ((FL)DB) and 38% in case of V bracing
system ((FL)VB). This revels that provision of bracing
reduces the time period and helps to control the SSI effect.

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Table 6 Results obtain using SAP 2000 for steel scaled down model

Scaled down Model	Case	Notation	Natural frequency (Hz)	Time period (S)
G+3	1	FB	8.02	0.1246
	2	(FL)BF	6.03	0.1658
	3	(FL)DB	11.82	0.0846
	4	(FL)VB	13.64	0.0733
G+5	1	FB	6.20	0.1612
	2	(FL)BF	4.77	0.2097
	3	(FL)DB	8.56	0.1168
	4	(FL)VB	8.68	0.1152
G+7	1	FB	4.54	0.2202
	2	(FL)BF	3.45	0.2894
	3	(FL)DB	5.42	0.1844
	4	(FL)VB	5.87	0.1703
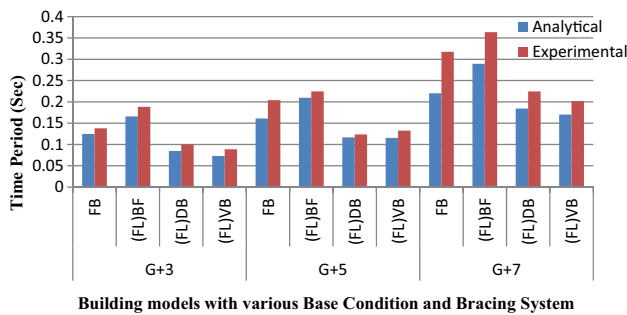
Fig. 10 Variation of natural time period-scaled down Steel model

From the study it is observed that V bracing are more effective as it produces min time period.

From Fig. 11, it is also observed that for G+3 building frame the time period obtained experimentally is higher than analytical study. For fixed base condition the experimental study is almost 18% higher than analytical study.
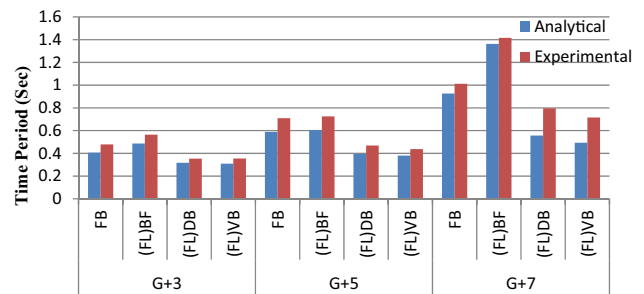
Fig. 11 Variation of natural time period-prototype structure

For flexible base also same trend is observed. For bare frame, diagonal braced frame and V braced frame the time period by experimental study is 16, 12 and 15% higher than analytical study respectively. The above all observation indicates that for all the cases experimental study yield

Table 7 Results for prototype structure

Prototype structure	Case	Notation	Natural frequency (Hz)		Time period (S)	
			Converted from exp. study	Analytical study	Converted from exp. study	Analytical study
G+3	1	FB	2.048	2.465	0.4882	0.4056
	2	(FL)BF	1.497	2.058	0.668	0.4859
	3	(FL)DB	2.824	3.152	0.3541	0.3173
	4	(FL)VB	3.177	3.24	0.3147	0.3084
G+5	1	FB	1.384	1.6989	0.7225	0.5886
	2	(FL)BF	1.257	1.653	0.7955	0.6051
	3	(FL)DB	2.133	2.529	0.4688	0.3954
	4	(FL)VB	2.288	2.636	0.4370	0.3793
G+7	1	FB	0.889	1.080	1.123	0.9257
	2	(FL)BF	0.777	0.898	1.287	1.114
	3	(FL)DB	1.398	1.798	0.7955	0.5562
	4	(FL)VB	1.257	2.023	0.7153	0.4942

almost 12–18% higher time period than analytical study. Almost same trend is observed for G+5 and G+7 steel scaled down model.

Conclusion

The following conclusions have been derived from the study:

1. SSI effect causes increase in the time period of structure.
2. In the present study for soil under consideration for the prototype building frame G+3, G+5 and G+7, the time period increases in the range of 15–18% as obtained by experimental study and by 5–10% as obtained by analytical study. This reveals that experimental study produces higher time period than analytical study. This is obvious because of soil mass simulation in the laboratory which in spite of all possible care the real time soil mass simulation is not possible in the laboratory.
3. The variations in experimental and analytical results are possible due to one or all of (a) The idealistic material properties in the analytical study are not matching with the material of model. (b) The idealistic stiffness of joints difficult to reproduce in the model. (c) The theoretical boundary condition may not possible to reproduce in the experimental study. (d) Due to repeated test the performance of the model is likely to vary. This is due to geometrical distortion of the model or fatigue developed in the model.
4. The SSI results into the increase in the time period leading to high lateral displacement which in turn results to P-Δ effect causing distress to structure. The effect of SSI is observed to be controlled by providing bracing in the structure. The study reveals that both diagonal and V bracing are effective. Among these V bracing are observed to be marginally more effective than diagonal bracing. This inference is based on various building frames considered for the study for the soil under consideration. However in order to derive more comprehensive conclusion study needs to be carried out on verity of building frames resting on various types of soil.
5. The present study demonstrates that, it is possible to estimate the various parameters of the prototype structure by performing the test on scaled down models and mapping the results to prototype structure using similitude laws. This will assist to evaluate most realistic behavior of prototype structure.
6. The actual performance of the model is possible to investigate by conducting the test under the typical earthquake by providing the time history to shake table.

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