Effect of Structure-Soil-Structure Interaction on Seismic Response of Adjacent Buildings

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***Abstract*—During Earthquake Ground Motion, adjacent structures interact with each other through the surrounding soil media. This phenomenon is termed as Structure-Soil-Structure Interaction (SSSI). Most of the work reported in literature, in this area, is confined to soft, medium soft and hard soils in foundation. Nothing much is reported on the effect of Sandy-Silty-Clay soils present beneath the foundation of adjacent structures. In this work an attempt has been made to study the response of adjacent structures when founded on such soils. Two adjacent multi-storey buildings of 11 storeys, 36m in height having plan dimensions of 16mx16m are considered in the study. SAP 2000 has been used as modeling and analysis software tool. Raft foundation and soil around the foundation is modelled with 8-noded elastic solid element with three degrees of freedom at each node. The soil mass considered has a size of 1.5 times the width of the foundation along both directions and thickness of 30m. Seismic analysis of two adjacent multi-storey buildings has been carried out for all zones using response spectrum method of IS 1893-2002 (Part-I) considering Structure-Soil-Structure Interaction (SSSI). Single multi-storey building on similar soil strata is also analyzed apart from analysis of conventional fixed base building models for comparison. It is found that adjacent building influences the seismic response of the structure quite significantly under such soil medium present beneath the foundation.**

Keywords*— Structure-Soil-Structure Interaction; Adjacent Buildings; Raft Foundation; SAP 2000;

I. INTRODUCTION

Due to increase in population land availability being limited, resulted in construction of buildings at closer spacing. In design offices, seismic resistant design of buildings the base is assumed as fixed at ground level during analysis, which is good enough for and light structures erected on stiff soils. But in case of stiff and heavy structures supported on soft soil it leads to conservative results. The interactions among a structure, its foundation, and the surrounding soil are collectively referred to as soil-structure interaction. During major earthquakes, it is observed that some buildings are damaged because of interactive response of the buildings which are built very close to them. Adjacent structures may also interact with each other through the soil during an earthquake. Interaction between adjacent foundation-structure systems through the surrounding soil is referred to as Structure–Soil–Structure interaction (SSSI). Modern design codes are silent about considering structure-soil-structure interaction effects. Many experimental and analytical studies have shown that Structure-Soil- Structure Interaction effects are significant for multi-storey buildings resting on soft soil deposit than hard rock foundations.

Mahmoud Yahyai et al., (2008) [9] Showed that the response of the buildings increases due to the interaction effects. Two adjacent 32 story frame buildings with concrete shear walls resting on soft clay, sandy gravel and compacted sandy gravel are considered.

Farhad Behnamf A R et al., (2014) [5] showed that pounding force increases for smaller clear distances. Soil flexibility reduces the displacements and decreased the storey shear in all stories. Nonlinear time history analysis is done and compare the variation of structures nonlinear responses (story drift, shear).

Very few investigations have been done on interaction effects of adjacent buildings. The present study focuses on structure-soil-structure interaction effects of two similar adjacent reinforced concrete multi-storey buildings founded on sandy-silty clay soil beneath the foundation. Single building on similar soil is also analyzed for earthquake ground motion apart from fixed base model. Responses such as maximum displacement, base shear and modal time period are studied.

II. MODELING AND ANALYSIS

A. *Description of the Building*

A G+10 storey reinforced concrete moment resisting frame building is considered. The building is assumed to be a residential apartment building and it has plan dimension of 16 m X 16 m and the height of 36 m from the ground level. The stilt floor is of 4 m height and all other storeys are of 3.2 m height. The plan showing location of columns and Centre lines of beams is shown in Fig. 1.

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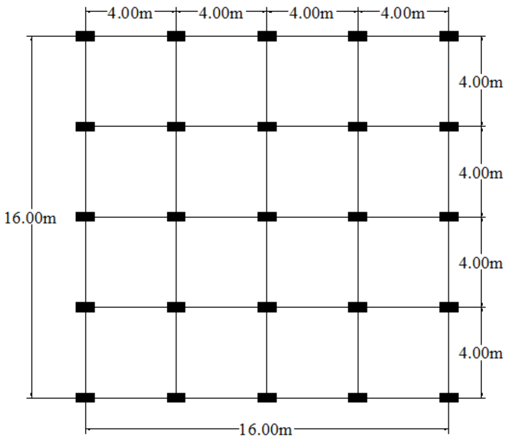

Fig. 1. Centre Line of Beams and Columns (Plan)

The dimensions of building components are as noted in Table 1.

TABLE I. DIMENSIONS OF COMPONENTS OF BUILDING

Properties	Beam	Column	Slab
Size (mm)	200 X450	200 X 450 200 X 600 300 X 600	150
Material	Concrete	Concrete	Concrete
Grade of Concrete	M25	M30	M25
Grade of steel	Fe 415	Fe 415	Fe 415

i. Loads

The building is assumed to be residential apartment building. Dead loads are taken as per IS: 875(Part 1)–1987 and Imposed loads are as per IS: 875(Part 2)–1987. The unit weights of materials and loads considered are listed as follows.

Unit weight of RCC =25.00 kN/m^3
Unit weight of solid concrete block masonry =20.50 kN/m^3
Weight of cement plaster =20.40 kN/m^3
Live load on each floor= 2 kN/m^2
Live load on roof=1.5 kN/m^2
Floor finish on each floor and roof=1.5 kN/m^2
Self-weight of 0.15m thick wall= 10.5 kN/m
Self-weight of 0.1 m thick wall = 7.6 kN/m
Self-weight of Parapet: = 3.5 kN/m

B. Finite Element Modeling

The building considered for study has been modeled using SAP 2000 as 3-Dimensional R.C. frame building using 3-D RC Beam and RC Shell elements. The 3-D beam elements have three translational and three rotational degrees of freedom at each node. Roof and floor slabs at various storey levels are modeled with R.C shell elements.

C. Building with Base as Fixed

The multistoried building is analyzed for fixed base condition. Fixed condition is obtained by restraining all six degrees of freedom for end node of column. Finite Element Model of Building with fixed base is shown in Fig. 2.

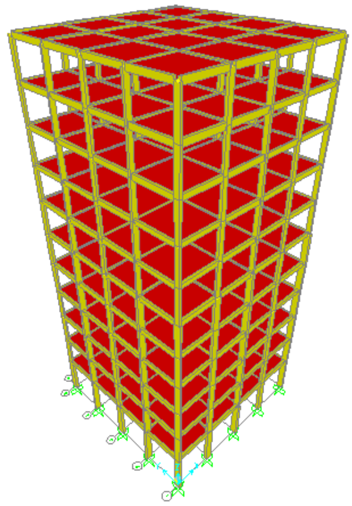

Fig. 2. Finite Element Model of Building (3D View)

D. Idealization of soil

The soil conditions considered are based on the details provided in soil investigation report prepared by M/s Nagadi Consultants. Soil profile indicates the presence of top surface layers of clayey-silty-sand to sandy-silty-clay, underlain by strata of silty clayey sand. These strata extend down to about 8.0 m to 10 m depth. Thereafter, the subsoil encountered is clayey silty sand to silty sand with clay. The present study considered the Sandy-silty-clay soil to facilitate flexibility effects. The soil parameters for sandy silty clay soil is listed and shown in Table II.

TABLE II. SOIL PARAMETERS AND CALCULATED VALUES

Soil Parameters	Notation	Formula	Calculated Values
SPT No.	N	5	5
Shear Wave Velocity	V_S	$100 \times N^{0.33}$	170.99 m/s
Unit Weight	γ	By soil test	18 kN/m^3
Mass Density	ρ	γ/g	1834.86 kg/m^3
Shear Modulus	G	ρV_S^2	53653 kN/ m^2
Poisson's Ratio	μ	0.3-0.35	0.3
Modulus of Elasticity	E	$2G(1+\mu)$	139497.8 kN/ m^2

E. Idealization of soil

Finite element method or Elastic Continuum method has been used to model the soil continuum. The soil continuum is idealized using 3-D, 8-noded elastic solid elements with three degrees of freedom at each node. Soil is treated as a homogeneous, isotropic, elastic medium and mass less. Raft foundation of 17m x 17m and a depth of 0.6m is considered. The width of the soil medium is taken as 1.5 times the width of the raft foundation and thickness of soil medium is taken as 30m. Vertical translation has been arrested at the bottom boundary while lateral translation has been arrested at the vertical boundaries. Elastic continuum model of building with Raft and Soil is shown in the Fig.3.

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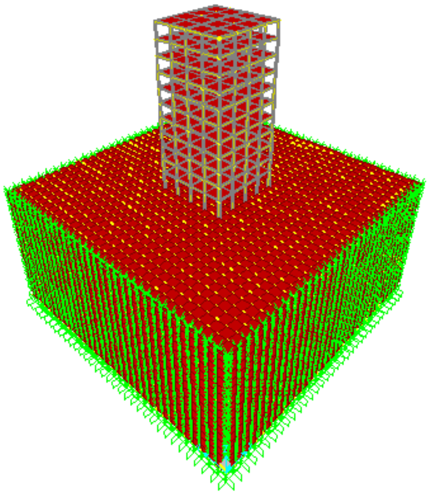

Fig. 3. Elastic Continuum Model of Building with Raft and Soil

F. Adjacent Building with SSSI

Two similar adjacent buildings with separate raft foundation are considered. As per Clause 7.11.3 of IS 1893: 2002 (part I), the separation distance between two adjacent structures is given by R (Response Reduction Factor) times the sum of the calculated storey displacements as per Clause 7.11.1.

The maximum displacement obtained in single building with SSI along longitudinal direction is 108.9 mm. The computed minimum distance between the buildings as per code is 1.08 m. Hence it is assumed that two buildings are at a clear distance of 1.5m in longitudinal direction to avoid damage when two buildings deflect towards each other.

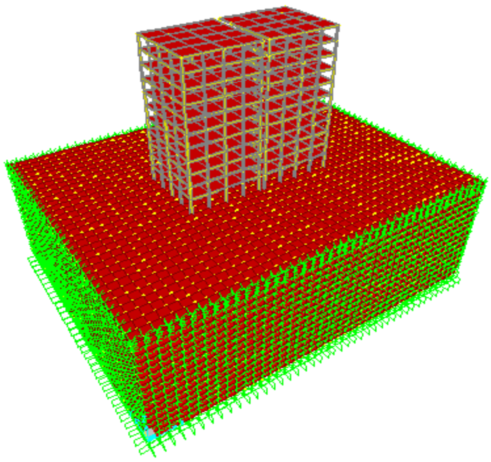

Fig. 4. Elastic Continuum Model of Building with Raft and Soil (3D View)

Seismic analysis of multi-storey buildings has been carried out for all seismic zones of IS 1893-2002 (Part-I) using response spectrum method analysis with response reduction factor of 5, importance factor of 1 and damping of 5% is considered for the present study.

III. RESULTS AND DISCUSSIONS

Seismic response has been studied with respect to Maximum displacement, base shear and modal time period of the building with fixed base for soft soil, building with SSI (flexible base), and adjacent buildings with SSSI founded on Sandy-silty-clay soil for all seismic zones of IS1893:2002.

A. Maximum Displacement

The lateral displacement obtained from the response spectrum analysis of structure for fixed base (without SSI), flexible base (with SSI) and adjacent building (with SSSI) conditions are tabulated in Table III. Comparison of maximum displacement shown in Fig.5.

It is observed that similar variations have been observed in all seismic zones. Maximum displacement has increased by 1.59 times in single building with SSI and 1.96 times in adjacent building with SSSI compared to building without SSI (fixed base).

TABLE III. MAXIMUM DISPLACEMENT RESULTS

Seismic Zones	Maximum displacement (mm)		
	Fixed Base	Flexible Base	
		Single	Adjacent
II	19.01	30.28	37.4
III	30.42	48.44	59.84
IV	45.63	72.66	89.75
V	68.45	108.99	134.63

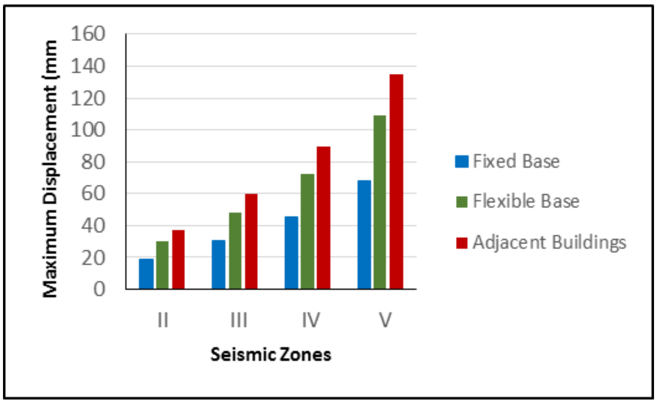

Fig. 5. Comparison of Maximum Displacement

B. Base Shear

It is the total design lateral force at the base of a structure. It is a function of mass, stiffness, height and modal period of the structure. The base shear results of three conditions are tabulated in Table IV. Comparison of Base Shear values shown in Fig.5.

TABLE IV. BASE SHEAR RESULTS

Seismic Zones	Base Shear in kN		
	Fixed Base	Flexible Base	
		Single	Adjacent
II	296.27	350.98	421.84
III	474.04	561.57	674.98
IV	711.05	842.365	1012.5
V	1066.58	1263.54	1518.74

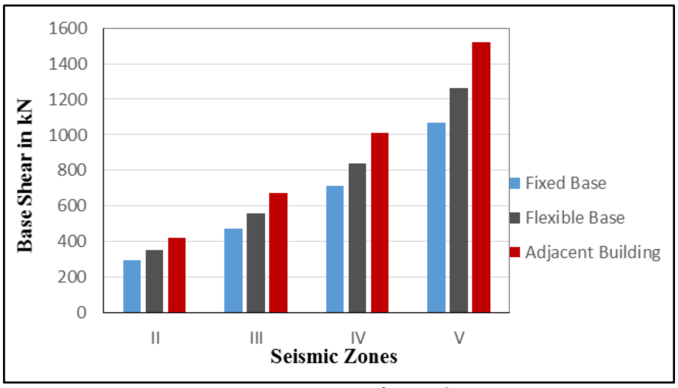

Fig. 6. Comparison of Base shear

Similar variations have been observed in all seismic zones. It has been increased 1.18 times for flexible base condition and 1.42 times for adjacent building condition when compared to fixed base condition. The increment is 1.20 times for adjacent building case compared to flexible base condition.

C. Modal Time Period

In modal analysis the building is analyzed as a continuous model with infinite number of freedom and natural frequencies. The time periods obtained from the analysis of three conditions are shown in Table V.

It is observed that mode 1 shows maximum time period in all three cases, adjacent building shows maximum time period in all modes. It is observed an increase of 1.3 times compared to fixed base case and 1.07 times compared to flexible building case in first mode.

TABLE V. MODAL TIME PERIOD RESULTS

Mode No.	Modal Time Period		
	Fixed Base	Flexible Base	
		Single	Adjacent
1	3.044	3.679	3.964
2	3.030	3.661	3.940
3	2.719	3.247	3.929
4	1.040	1.204	3.915
5	1.038	1.201	3.495
6	0.935	1.077	3.394
7	0.594	0.669	1.306
8	0.594	0.668	1.306
9	0.540	0.608	1.304
10	0.412	0.448	1.302
11	0.411	0.447	1.174
12	0.374	0.407	1.173

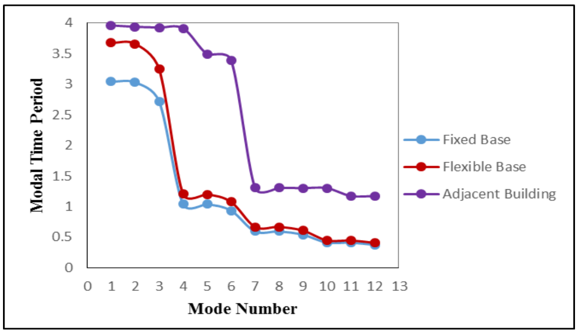

Fig. 7. Comparison of Modal Time Period

IV. CONCLUSIONS

In the current study, in order to study effect of soil structure interaction on seismic responses of adjacent buildings, the response spectrum analysis of an 11-storey RCC residential apartment building with a similar adjacent building with separate raft foundation founded on sandy-silty-clay soil medium (with SSSI) has been carried out. These responses are compared with results of response spectrum analysis of similar building founded on similar soil considering the effect of SSI (flexible base) and a similar building without considering soil-structure interaction (SSI) having fixed base. The effect of SSI and SSSI has been incorporated by using elastic continuum method and analysis has been carried out for all seismic zones of IS 1893:2002 using finite element method with SAP 2000 as a software tool.

The following conclusions were drawn after comparing the responses of three conditions.

- Maximum lateral displacement has increased by 96% in case of SSSI of adjacent buildings and by 59% in single building with SSI compared to building without SSI, i.e., a fixed base building.
- SSSI due to adjacent building has increased the maximum deflection by 23% in comparison to single building with SSI in sandy-silty-clay soils which is considerable and needs attention of designers.
- The base shear has increased by 42% in case of SSSI of adjacent buildings case in comparison to non-SSI fixed base buildings. In case of single building with SSI considered it has increased by 18%. A 20% increase is therefore occurs due to presence of adjacent building due to SSSI.
- The Natural Modal Time period has increased by 30% in case of SSSI due to adjacent buildings while it is 10% in case of SSI of single building when compared to non-SSI buildings with fixed base. Similar trend is observed over all 12 modes.
- Significant increase in response of multi-storey building under SSSI occurs compared to buildings under SSI and fixed base buildings due to effect of both soil-induced flexibility and influence of adjacent structure.
- It is necessary to consider the influence of adjacent structures founded on soft soils in analysis of multi-storey buildings for seismic response.

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