

Comparative Study on Building Frames with and Without Soil Structure Interaction Subjected to Seismic Forces

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ABSTRACT: The present scenario in seismic analysis of a structure is carried out by assuming the column bases to be fixed. In reality, the supporting soil medium influences the behaviour of the structure due to its ability to undergo deformation whereas fixed support ignores these deformations. Current study aims at understanding the effect of Soil Structure Interaction (SSI) in the seismic analysis of a structure. A G+10 symmetrical building with isolated footing resting on medium soil is taken for study. Dynamic linear analysis is performed for the building frames as per IS 1893(part I)-2002 using SAP 2000 software. The SSI is incorporated in the analysis by modelling the soil providing equivalent springs in six degrees of freedom as per George Gazetas formulae and comparison is made between fixed base model and SSI model. From the study it is observed that, there was significant increase in the response of the building from fixed support model to SSI model and the area of column reinforcement demanded by SSI model is more. Depending upon the changes in flexibility of the soil, accordingly the response of the building was also altered. The SSI model with footings of uniform dimension increases the seismic response compared that of with different dimensions. The comparative analysis therefore concludes that conventional method of analysing a structure presuming fixed support is not adequate to assure the structural safety for the buildings especially founded on relatively flexible soil.

KEYWORDS: Soil Structure Interaction, Seismic response, Isolated footing, Linear dynamic analysis, SAP 2000

I. INTRODUCTION

Earthquake refers to vibrations caused by random motion of the ground. The structural displacements and the ground displacements during earthquakes are dependent on each other. However, the typical practice is to adopt a fixed base for the analysis and design of a building. The behaviour of any structure is considerably affected by the supporting soil medium due to its ability to deform. In early times, the land which offers hard soil were used for the construction of structures as it provides a rigid platform for the structures resting on it and the land with soft soil sediments were avoided as it provides flexible support for the structures resting on it which is not suitable for the construction. But in this era of fast growing urbanisation, structures are constructed on available relatively soft soil because of paucity of land which is otherwise regarded to be unsuitable for the construction. This calls upon for the consideration of Soil Structure Interaction (SSI). The importance of considering SSI in the seismic analysis of structures is well demonstrated from the imprints of previous earthquakes discarding the effect of soil. From the reports of past earthquakes, including the 2001 Bhuj earthquake ($M=7.7$), the 1994 Northridge earthquake ($M=6.7$), the 1995 Kobe earthquake ($M=6.8$), the 1940 El Centro ($M=6.9$), the 1985 Mexico ($M=8.0$) etc., various damages have been noticed due to not accounting the effect of interaction in the analysis [7]. SSI can be ignored for the theoretical condition of a structure supported on rigid soil. Evaluation of SSI can be categorized as direct approach and sub structure approach. In direct

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approach, the soil and structure are included within same model and are analysed as a complete system. In substructure approach, the SSI problem is broken down into distinct parts and is combined to formulate the complete solution.

II. OBJECTIVES

The usual method of analysing a structure is carried out by presuming the base to be fixed. Nevertheless, the supporting soil medium also varies the seismic loading and lateral forces acting on a structure. The importance of considering SSI in seismic analysis of structures is well explained from the lessons learnt from past earthquakes neglecting the effect of SSI in the analysis. Seismic response of a structure due to SSI depends upon the properties of both soil and the structure. The following objectives are defined in order to illustrate the effect of considering SSI in seismic analysis of the structure.

1. To study the behaviour of buildings under earthquake excitation with and without Soil Structure Interaction provided with isolated footings.
2. To compare the area of reinforcement required for the building with or without Soil Structure Interaction.
3. To study the effect of Soil Structure Interaction under seismic forces for various modulus of elasticity of soil.
4. To study the effect of Soil Structure Interaction for building frames provided with isolated footings having same dimensions and with different dimensions.

III. METHODOLOGY AND STRUCTURAL MODELLING

A G+10 building, with ordinary moment resisting frames in two orthogonal directions, is selected for the study. It is considered to be located in Zone V on medium stiff soil, as per IS 1893: 2002. The buildings are modelled using SAP2000 software and dimensions of the members are selected based on the design of the building for gravity loads.

- ❖ A G+10 building is designed for gravity loadings only, the designed beam and column details such as sizes and reinforcement details are assigned for seismic analysis.
- ❖ The dynamic linear analysis is carried out for the series I model to study the structural behaviour when subjected to seismic forces, provided with fixed support at the column bases.
- ❖ In order to incorporate SSI in the analysis with reference to spring model approach, an additional load combination which implies to foundation is assigned to the building model and are analysed.
- ❖ Based on the column reactions from the analysis results, isolated footings are provided for safe bearing capacity of soil 250 kN/m², SSI in terms of surface spring stiffness are calculated using George Gazetas formulas, assigned for the isolated footing and are analysed to know the response of the structure.
- ❖ Series II models, building frames with SSI are analysed in the similar manner as mentioned above with change in modulus of elasticity of medium soil for 35000 kN/m² as E35, 50000 kN/m² as E50 and 65000 kN/m² as E65 respectively to study the variations in the structural behaviour associated with it.
- ❖ Series III models, building frames with SSI are analysed similarly to evaluate the effect of SSI for isolated footings having same dimensions as FSD and with different dimensions as FDD.
- ❖ For the idealization of the spring model, the effect of SSI is incorporated by providing equivalent springs along six degrees of freedom as shown in fig1. George Gazetas [14] has presented the complete set of algebraic formulas for readily computing the dynamic stiffness (K) as shown in Table I.

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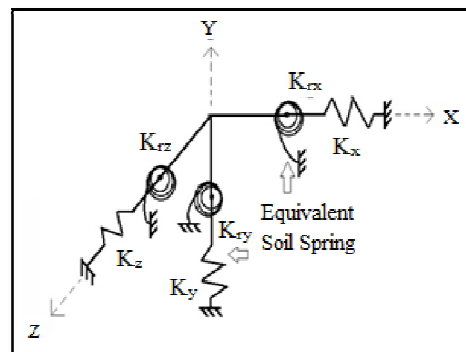


Fig 1: Equivalent spring stiffness along six degrees of freedom [14]

Where,

K_x, K_y, K_z = Stiffness of equivalent soil springs along the translational degrees of freedom along X, Y and Z axis.

K_{rx}, K_{ry}, K_{rz} = Stiffness of equivalent rotational soil springs along the rotational degrees of freedom along X, Y and Z axis.

Table I: Surface Spring stiffness formulae as per George Gazetas [14]

Degrees of freedom	Equivalent surface spring stiffness
Vertical	$[2GL/(1-\nu)](0.73+1.54\chi^{0.75})$ with $\chi = A_b/4L^2$
Horizontal(lateral direction)	$[2GL/(2-\nu)](2+2.50\chi^{0.85})$ with $\chi = A_b/4L^2$
Horizontal(longitudinal direction)	$[2GL/(2-\nu)](2+2.50\chi^{0.85})-[0.2/(0.75-\nu)]GL[1-(B/L)]$ with $\chi = A_b/4L^2$
Rocking(longitudinal direction)	$[G/(1-\nu)]I_{bx}^{0.75}(L/B)^{0.25}[2.4+0.5(B/L)]$
Rocking(lateral direction)	$[3G/(1-\nu)]I_{by}^{0.75}(L/B)^{0.15}$
Torsion	$3.5G I_{bz}^{0.75}(B/L)^{0.4}(I_{bz}/B^4)^{0.2}$

Where,

A_b = Area of the foundation considered.

B and L = Half-width and half-length of a rectangular foundation.

I_{bx}, I_{by} , and I_{bz} = Moment of inertia of the foundation area with respect to longitudinal, lateral and vertical axes.

Table II: Modelling and loading details

Type of building	General
Bays along X	8 at each 4 m
Bays along Y	8 at each 4 m
Storey height	3.2 m
Plinth height from foundation	2.5 m
Slab	150 mm
Beams	300 mm x 450 mm

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Column		500 mm x 500 mm
Wall		230 mm
Parapet height		750 mm
Unit weight of concrete		25 kN/m ³
Unit weight of brick		20 kN/m ³
Storeys	Live load	4 kN/m ²
	Finish	0.75 kN/m ²
Roof	Live load with access	2 kN/m ²
	Finish	1.5 kN/m ²
Footing	Isolated square footing	3.5 m x 3.5 m with 0.5 m depth
Soil	Modulus of Elasticity	35000 kN/m ² , 50000 kN/m ² and 60000 kN/m ²
	Poisson's ratio	0.4

The building models are grouped into three series bases on the objectives considered for the study.

Series I: Building model with and without SSI.

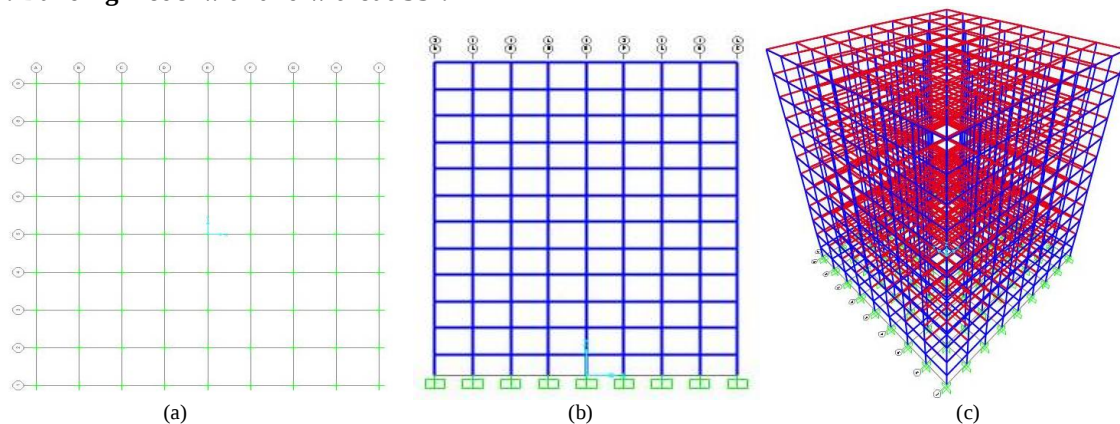


Fig 2 (a,b,c): Plan, elevation and 3D view of building model with fixed base

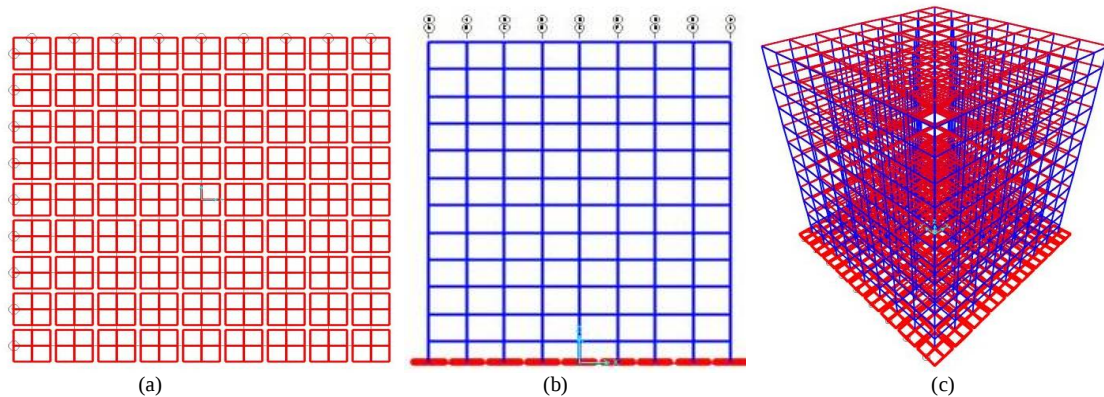


Fig 3 (a,b,c): Plan, elevation and 3D view of building model with SSI

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Series II: Building models with SSI considering varying modulus of elasticity of soil.

The buildings are modelled with SSI considering varying modulus of elasticity of medium soil i.e. E35, E50 and E65.

Table III: Spring stiffness for different modulus of elasticity of soil

Surface Spring stiffness in kN/m			
Modulus of Elasticity in kN/m ²	E - 35000	E - 50000	E - 65000
Translation(Vertical direction), U1	165520.83	236458.3	307395.8
Translation(Horizontal lateral direction), U2	123046.88	175781.3	228515.6
Translation(Horizontal longitudinal direction), U3	123046.88	175781.3	228515.6
Rotation(about vertical axis), R1	48522.24	69317.49	90112.74
Rotation(about horizontal lateral axis), R2	415621.70	593745.3	771868.9
Rotation(about horizontal longitudinal axis), R3	401767.68	573953.8	746139.9

Series III: Building models considering SSI provided with isolated footings having same dimension and with different dimensions.

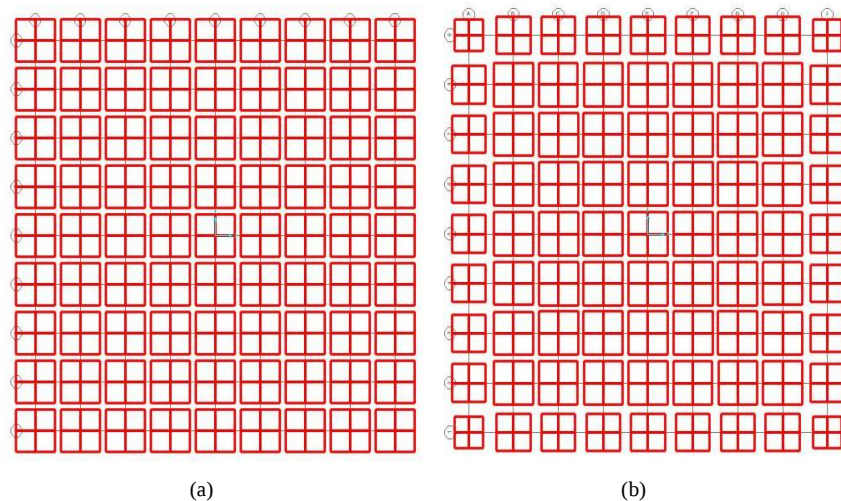


Fig 4 (a, b): Plan of SSI model with Isolated footing having uniform dimension of and different dimensions.

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IV. RESULTS AND DISCUSSIONS

1. Structural behaviour of building models with or without SSI.

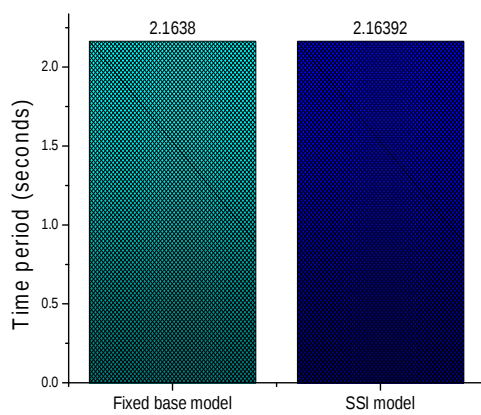


Fig 5: Variation in Time period for fixed base model and SSI model

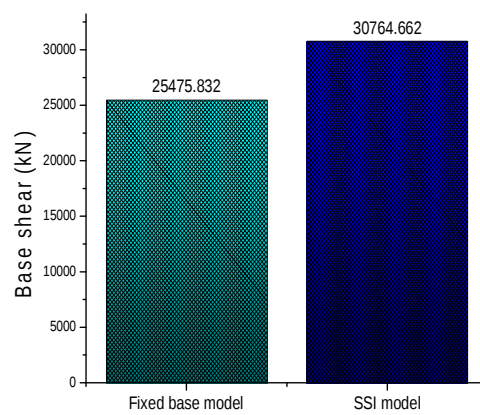


Fig 6: Variation in Base shear for fixed base model and SSI model

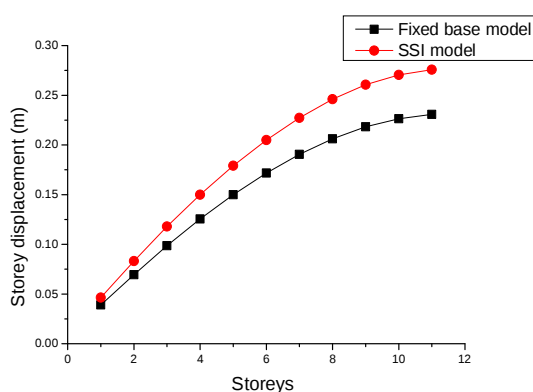


Fig 7: Variation in Storey displacement for fixed base model and SSI model

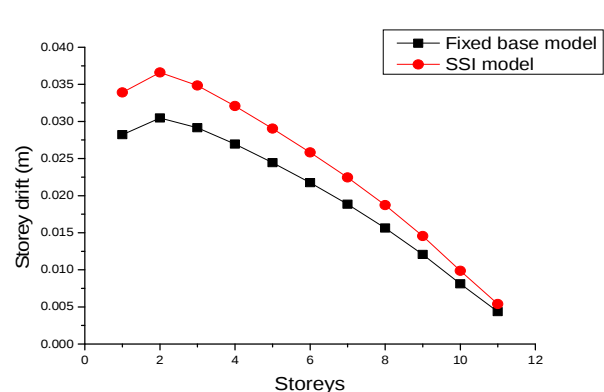


Fig 8: Variation in Storey drift for fixed base model and SSI model

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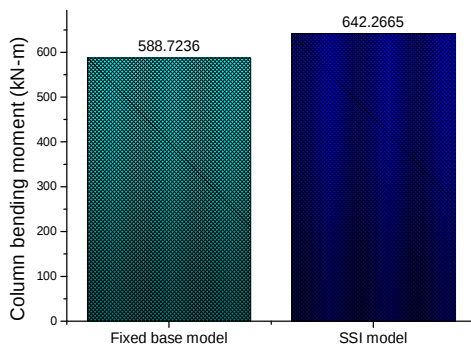


Fig 9: Variation in Column bending moment for fixed base model and SSI modelbase

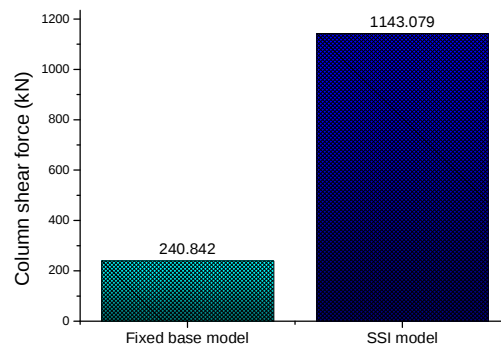


Fig 10: Variation in column shear force for fixed model and SSI model

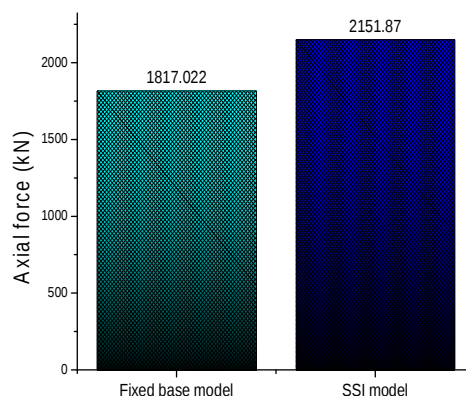


Fig 11: Variation in Column axial force for fixed base model and SSI model

The variation in time period is just marginal for fixed base model and SSI model. The increase in base shear is about 17.2% from fixed base model to SSI model. The storey displacements are gradually increased with increase in the number of storeys and this trend of increase is more in case of SSI model compared with fixed base model as the flexible base provided by the SSI model decreases the stiffness of the structure which results in an increased displacement. The increase in roof displacement is about 16.5% in SSI model in comparison with fixed base model whereas the increase in storey displacements at bottom storeys is negligible. The storey drift shows a drastic increase by about 65% as the building is weakened at the ground storey due to the presence of an open ground storey accounting for reduction in stiffness of the structure, but it is strong in upper stories owing to large contribution of lateral stiffness by the infills and thus storey drift gradually decreases with increase in number of storeys. The increase in storey drift is more in case of SSI model when compared with fixed base model and it is about 17% increase at ground storey level in SSI model with fixed base model. The increase in column moment is about 9%, increase in column shear force is about 78% and the increase in axial force is about 16% from fixed base model to SSI model.

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2. Area of reinforcement for building model with and without SSI

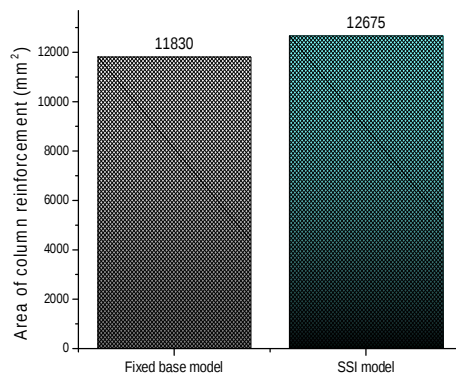


Fig 12: Variation in area of column reinforcement for fixed base model and SSI model for fixed base

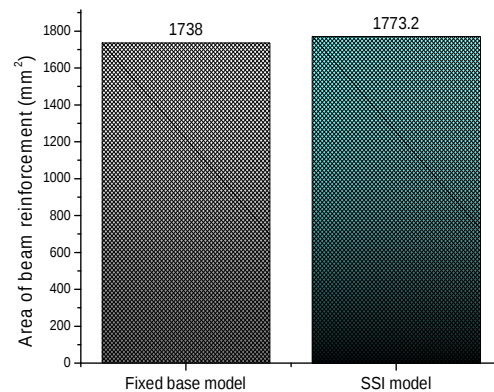


Fig 13: Variation in area of beam reinforcement model and SSI model

When SSI is incorporated in a building model, the rigidity of base of the building is reduced which ends up in affecting the strength and stiffness parameters of the building in a decreasing manner resulting in more bending moment and shear force and hence more is the reinforcement demand in SSI model. The increase in area of column reinforcement is about 7% and the increase in area of beam reinforcement is about 2% from fixed base model to SSI model.

3. Effect of SSI for varying modulus of elasticity of soil.

The time period decreases with increase in modulus of elasticity of soil due to increase in strength and rigidity of the soil which results in increase of overall stiffness of the structure. The decrease in time period from the model E35 to E50 is about 0.5% and from E50 to E65 is marginal. The increase in modulus of elasticity of soil helps in reduction of deformations, increase in rigidity and lesser displacements when subjected to seismic forces. Lesser the displacements less will be the spectral accelerations leading to reduced base shear. The decrease in base shear is about 10.3% from E35 to E50 and it is about 26% from E50 to E65 respectively. As the modulus of elasticity increases from E35 to E65, less is the storey displacement and the decrease is about 10.3% from E35 to E50 and 36% from E50 to E65. Similarly, the storey drift is decreased by about 12% from E35 to E50 and 36% from E50 to E65. The Column bending moment, shear force and axial force also decreases from E35 to E65. The decrease in the bending moment is about 9% from E35 to E50 and 25% from E50 to E65; the decrease in shear force is about 11% from E35 to E50 and is about 28% from E50 to E65; the decrease in axial force is about 9% from E35 to E50 and is about 26% from E50 to E65.

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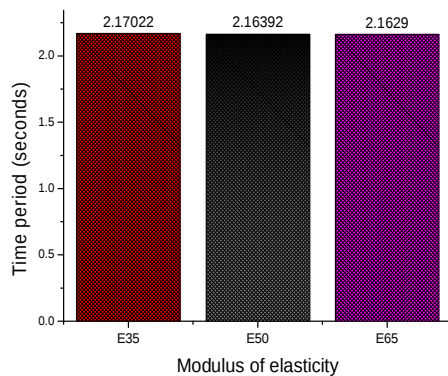


Fig 14: Variation in time period for different modulus of elasticity of soil

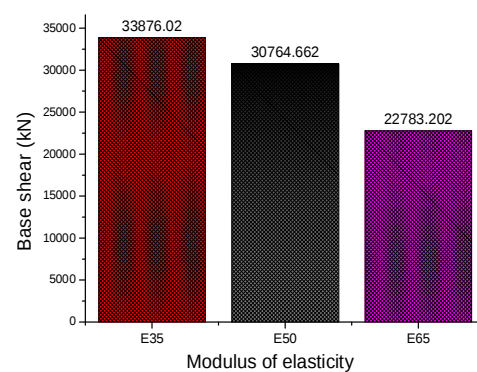


Fig 15: Variation in base shear for different modulus of elasticity of soil

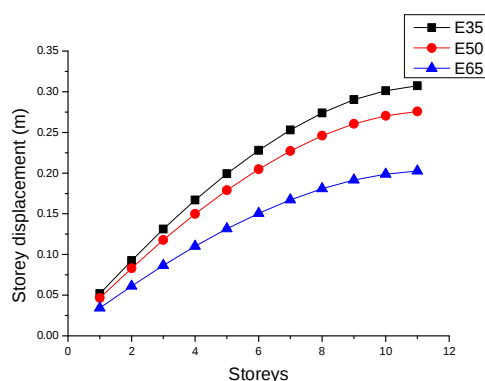


Fig 16: Variation in storey displacement for different modulus of elasticity of soil

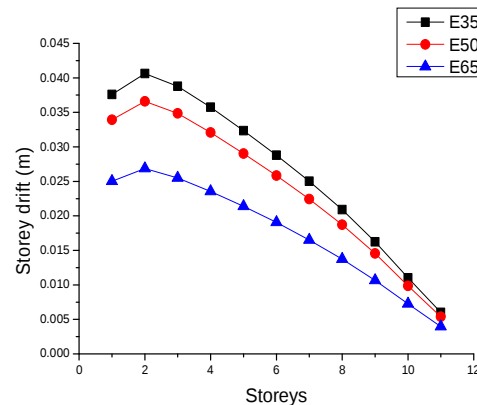


Fig 17: Variation in storey drift for different modulus of elasticity of soil

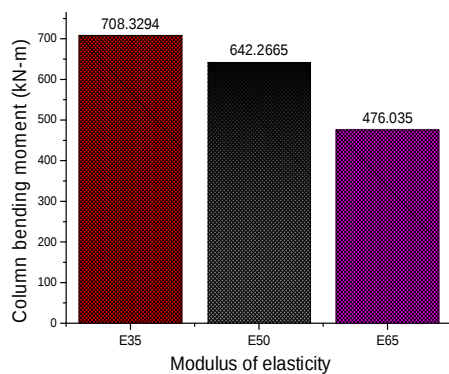


Fig 18: Variation in Column bending moment For different modulus of elasticity of soil

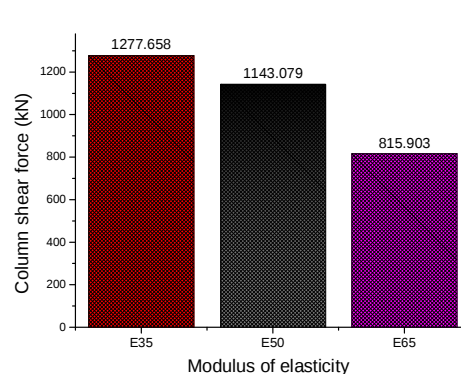


Fig 19: Variation in Column shear force for different modulus of elasticity of soil

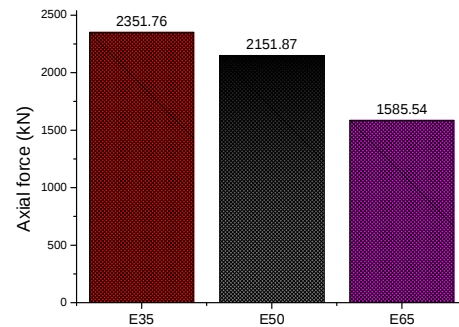


Fig 20: Variation in Column axial force for different modulus of elasticity of soil

4. Building frames considering SSI provided with isolated footings having same dimension and with different dimensions.

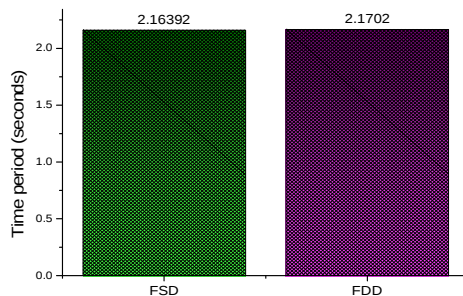


Fig 21: Variation in Time period for FSD and FDD model

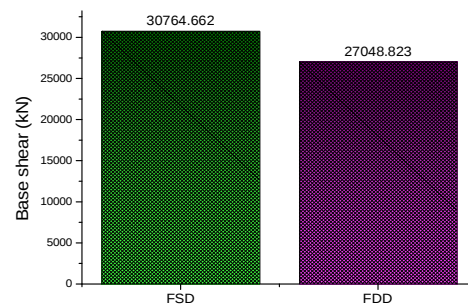


Fig 22: Variation in base shear for FSD and FDD model

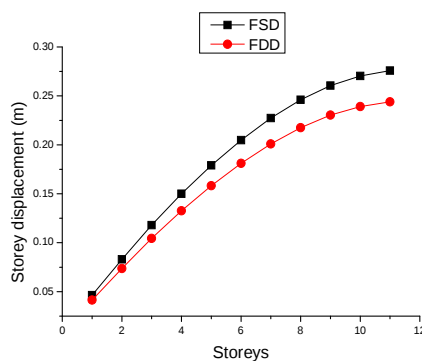


Fig 23: Variation in Storey displacement for FSD model and FDD model

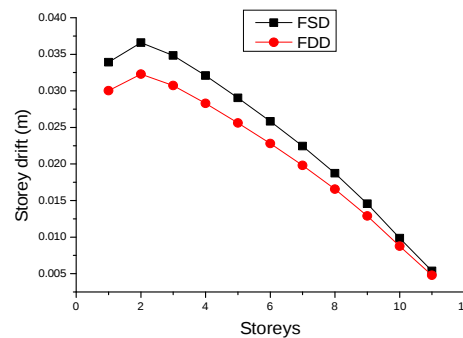


Fig 24: Variation in Storey drift for FSD model and FDD model

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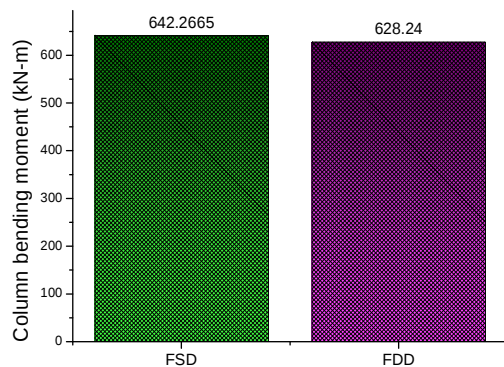


Fig 25: Variation in Column bending moment for FSD and FDD model

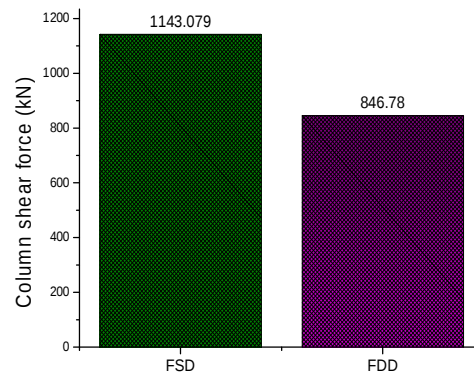


Fig 26: Variation in Column shear force for FSD and FDD model

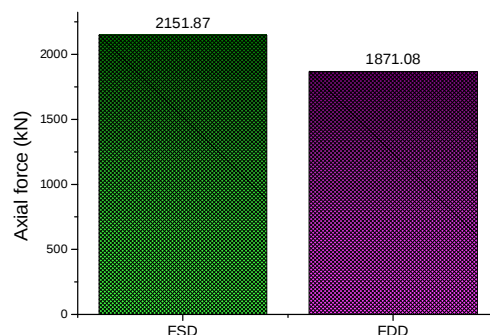


Fig 27: Variation in Column axial force for FSD and FDD model

The change in footing dimensions for SSI model does not show a significant effect in case of time period. The base shear decreases by about 12% from FSD to FDD model as FSD model provides more surface area for deformation than the FDD model. The decrease in storey displacement and storey drift is about 12% in FDD model in comparison with the FSD model. Since FDD model offers less area for deformation when subjected to seismic excitation, more will be the lateral resistance offered by the structure because of the strength of the structure owing to less bending moment, shear force and axial force. The decrease in column bending moment is about 3%, shear force is about 25% and axial force is about 13% from FSD to FDD model.

V. CONCLUSIONS

In this study, linear dynamic analysis is carried out for the building frames with fixed support and with SSI using SAP 2000 software as per IS 1893(part I) - 2002 [10]. The comparative results indicates that inclusion of SSI allows a flexible base due to the ability of the supporting soil medium to deform which ends up in significant increase of the seismic response of a structure when subjected to earthquake excitation.

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- The inclusion on SSI in the seismic analysis allows significant changes in the seismic response of a structure compared to the conventional fixed base model.
- The increase in Natural time period in SSI model is only marginal; whereas the other parameters like Base shear, Storey displacement, Storey drift, Column bending moment, Column shear force increases by 17.2%, 16.5%, 17%, 9% and 78% respectively. Hence, evaluation of these parameters neglecting SSI may lead to factual error in the seismic design.
- The strength and stiffness parameters of the structure reduce considerably with the incorporation of SSI in the seismic analysis which results in requirement of more reinforcement. The area of column reinforcement demanded by SSI model is 7% more than the fixed base model.
- The seismic response of a structure decreases with increase in modulus of elasticity of the soil making the soil stiffer with reduction in flexibility.
- The isolated footings of uniform dimension provided in SSI model allows more surface area for deformation which leads to marginal increase in time period whereas increase in base shear, Storey displacement, Storey drift is about 12% and increase in Column bending moment, shear force and axial force is about 3%, 25% and 13%; Grouping of isolated footings to different dimensions as required is therefore preferable.
- Finally the study concludes that, the conventional method of analysing a structure neglecting SSI is not adequate to assure the resistance against lateral forces when subjected to seismic excitation especially when founded on relatively flexible soil.

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