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Soil-Structure Interaction of RC Building for Different Types of Soils Considering the Mohr-Coulomb Soil Model

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ABSTRACT: Soil-Structure interaction plays a significant role in the design of the structure. The coupling effect between the structure and soil media is termed as soil-structure interaction. Conventional design practice needs to modify based on the soil-structure interaction effect and must be included in the standards of regular design practices. The study is specifically focused on the soil-structure interaction of the G+3 building for three different types of soil i.e., hard soil, medium soil, and soft soil considering the Mohr-Coulomb soil model using finite element-based software ANSYS. The effect of soil-structure interaction is observed on the vertical reaction, horizontal reaction, and bending moment at the footing base considering the Mohr-Coulomb soil models. The parameters are observed at the corner, edge and central footing of the building. To observe the effect of soil-structure interaction, flexible base model is compared with fixed base model. The effect of the SSI increases as the soil changes from hard to soft soil. The variation of parameter with location of the footing are studied, which shows the vertical reaction at central footing shifts towards outer footings i.e., edge and corner footings while the central footing shows a greater intensity of horizontal reaction and bending moment compared to edge and corner footings.

Keywords: Soil-Structure Interaction, Mohr-Coulomb soil model, finite element method, foundation reactions etc.

INTRODUCTION

Soil structure interaction is defined as the reaction of soil with respect to the behaviour of the structure and reaction of the structure with respect to motion in the soil. Soil structure interaction generally defines each entity's behaviour according to its properties. It can also be defined as the collective evaluation of the response of the superstructure, substructure, and soil media beneath the building. Such as contrast in the RC building, various parameters like time period, deformation, frequency, and equivalent stresses vary with respect to behaviour of soil. If not considered, these parameters affect the building detrimentally, signifying the soil-structure interaction. In the general design practice, SSI is not considered and no proper codal provision can ease the design procedure. Several studies have been made on the soil-structure interaction which shows the significance of soil-structure interaction and recommended the proper codal provisions.

When a structure is subjected to a seismic force (seismic excitation), the interface between the soil and foundation, causing the ground motion to vary. Two sorts of phenomena or consequences might result from soil-structure interaction. i.e., kinematic interaction and inertial interaction. **Inertial interaction** refers to the SSI effect that is related to the structure's mass. The inertia forces (seismic acceleration times mass of the structure) created in the structure are the sole reason for the vibrational movement of the structure's masses. The forces of inertia that are applied to the structure lead to an overturning moment and a transverse shear. **Kinematic interaction** is defined based on the stiffness of the structure. By assuming that the structure and foundation have stiffness but no mass, the deformation produced by kinematic interaction alone can be estimated. It occurs when the stiffness of the foundation system obstructs the initiation of the free field motion.

The approaches used to evaluate the soil-structure interaction are the direct approach and the sub-structure approach. The **direct method** is the most well-known. This method employs a full structure–pile-soil system, in which the soil resistance around a pile is described using a spring or a finite element system. When the accuracy of the spring model is proven by comparison with other approaches, it is known to be practical. The **sub-structure method** is another well-known and useful technique. The engineering bedrock input is used to compute the free-field ground motion, which is then re-input to the structure–pile system. Simply superposing the response (kinematic response) due to forced displacement of the free-field ground and the response (inertial response) owing to the inertial force from a superstructure is the goal of this approach. In the substructure method, there are two methods: i.e., the static method and the dynamic method. SSI evaluation can be done using the FEM software by considering the various constitutive models. Here below some kinds of literature are mentioned which have been done before, to contrast the areas of soil-structure interaction and its significance.

The study is concerned with the Mohr-Coulomb model of the soil which is a perfectly plastic elastic model. To achieve the above objectives a G+3 RC building is modelled and analysed for different types of soils and soil models using ANSYS software. The vertical reaction, horizontal reaction, and bending moment at footing base are calculated for different models and compared for useful research findings.

Anjali B. and Raji M. (2015) analysed a G+12 building model with different types of footing founded on 3-layered soil underneath. They found that the piled-raft foundation behaves more satisfactorily under the Soil-Structure Interaction condition. Shanmugam et.al (2015) the impact of Soil-Structure Interaction on a four-storeyed two-bay frame founded on a pile is analysed considering the embedment of cohesive soil. Alice M. and Nimisha A.S. (2017) found the significance of the SSI using the 10-storeyed building founded on a piled-raft foundation on ANSYS Workbench v17.0. Vishwajit A. and Satish S.R. (2018) collected important information on SSI impact on buildings during the earthquake or the earthquake-prone areas. They have done case studies on earthquake-affected areas. Deepashree R. et.al (2020) paper contains the

SSI analysis of RC buildings to check the interdependency of ground motion and structure during the earthquake especially. Various models are prepared considering the 4th seismic zone and the parameters are found to access the impact of SSI.

Investigation Problem

The problem undertaken for the study is the 3bay X 3bay G+3 building having the isolated square footing founded on the flexible soil media under the effect of gravity load. Three different types of soil with varied properties based on the state of denseness are considered for the SSI analysis. Various models were prepared on the finite element-based software ANSYS workbench with the combination of different types of soil and a model with the fixed base configuration. The problem aims to analyze the Soil-Structure Interaction considering the different types of soil based on the Mohr-Coulomb soil model. Various parameters are considered for the SSI analysis. A flexible base model with different types of soil was compared with the fixed base model to evaluate the percentage impact of SSI on the building structure under gravity load concerning the fixed base model.

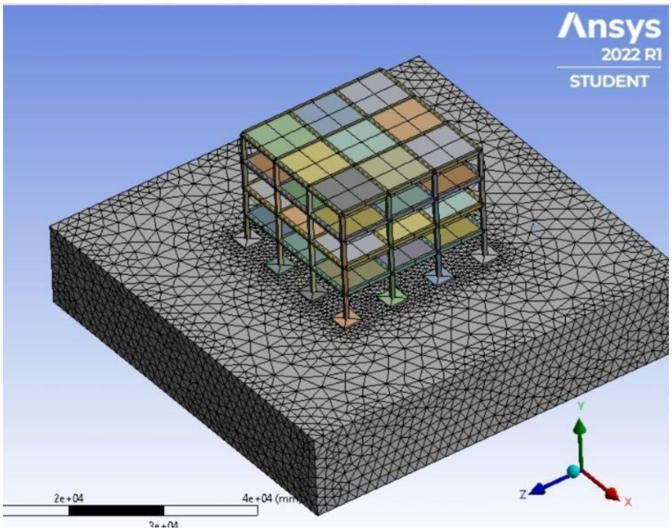

Figure 1: 3D view of the SSI building model

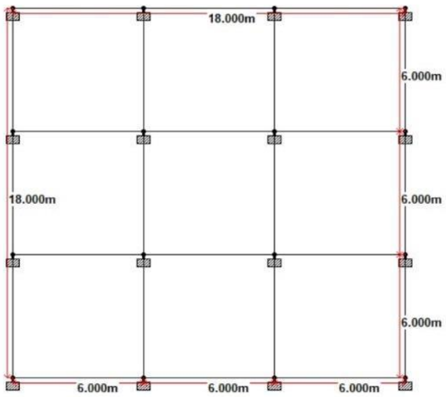

Figure 2: Top view of the fixed base building model

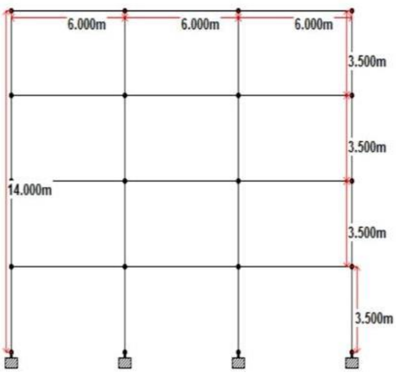

Figure 3: Elevation of fixed base model

Table 1: Data used for the analysis

Sr. No.	Description	Value/Type
1.	No. of Storey	3
2.	No. of bays in both directions	3
3.	Bay width	6 m
4.	Height of floor	3.5 m
5.	Beam size	300 mm X 500 mm
6.	Column size	500 mm X 500 mm
7.	Footing size	2.5 m X 2.5 m X 0.5 m
8.	Slab thickness	150 mm
9.	Thickness of finishes	50 mm
10.	Partition wall thickness	130 mm
11.	Outer wall thickness	230 mm
12.	Height of parapet wall	1 m
13.	Size of soil block	48 m X 48 m X 10 m
14.	Density of concrete	2500 kg/m^3
15.	Modulus of elasticity of concrete	30000 MPa
16.	Poisson's ratio of	0.18
17.	Bulk modulus	15625 MPa
18.	Shear modulus	12712 MPa
19.	Density of masonry wall	2000 kg/m^3

Loading condition and soil properties

The present study is carried out for the dead and live loads only for the analysis of the structure. Dead load is considered as the self-weight of the structural members, considered based on the IS code 875 part-1 1987, calculated based on the density of the material of structural member and value of live load is considered from IS 875 part 2 1987. Obtained loading is applied on given structural member using the ANSYS to simulate the real-life problem. The properties of soil are taken from different literature as per their utility in the soil-structure analysis. Selection of the soil properties is done based on the footing model in ANSYS to check the responses of soil with respect to varying each parameter by keeping all other parameters constant. The soil properties are used in present study which showed proper patterned responses as the standard results. Three different types of soil are taken for the experimental study of soil-structural interaction of the building and behavioural observations are taken to analyse the given problem.

Table 2: Loading conditions calculated

Sr. No.	Description	Value/Type
1.	Live load on the floor	4 kN/m^2
2.	Live load on the roof	1.5 kN/m^2
3.	Floor finish load	1 kN/m^2
4.	Outer wall load	13.8 kN/m
5.	Inner wall load	7.8 kN/m
6.	Parapet wall load	2.6 kN/m

Table 3: Properties of Soil

Sr. No.	Properties	Hard soil	Medium soil	Soft soil	Unit
1.	Density of soil	2064	1800	1667	kg/m^3
2.	Modulus of elasticity	80	35	25	MPa
3.	Poisson's ratio	0.35	0.30	0.25	
4.	Shear modulus	30.77	30.77	13.27	MPa
5.	Bulk modulus	66.66	66.66	28.75	MPa
6.	Cohesion	0.1	0.1	0.1	MPa
7.	Angle of internal friction	38	34	33	
8.	Angle of Dilatancy	8	4	3	

Software Validation

The observation is taken for the single-footing model of 2.5m X 2.5m with 1mm thickness on the 10m X 10m X 5m soil block. The C-ϕ soil is considered throughout the soil-structure interaction analysis in ANSYS software with varying state of denseness and the modulus of elasticity. The Mohr-Coulomb soil model is perfectly suitable for the C-ϕ soil. A soil of elasticity modulus 80MPa, Poisson's ratio 0.3, cohesion is taken as 0.1 MPa and the angle of internal friction, and dilatancy angle is taken as 34 and 4 degrees respectively. The model analyzed in ANSYS 2022 R1 and the results are compared concerning the immediate settlement concept from the IS 8009-1-1976.

$$S_i = \frac{qB(1-\mu^2)I_s}{E}$$

Where,

"q" is the load pressure in N/mm^2

"B" is the width of the footing in mm

"μ" is the Poisson's ratio of the soil

"E" Young's modulus of elasticity

"I_s" is the influence factor = 1.12 for flexible footing

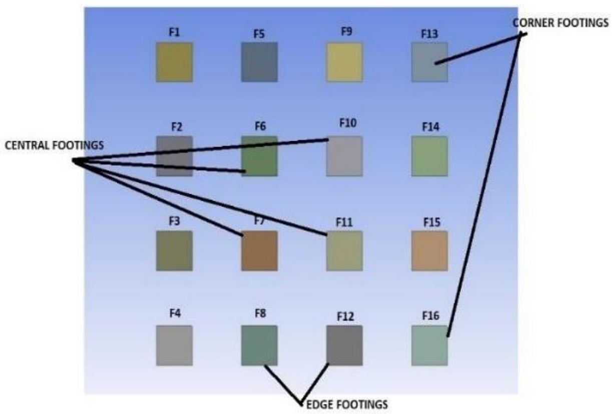

Figure 4: Description of footing positions of building model

Validation Statement

S.No	Description	Settlement (mm)
1	Elastic soil model (ANSYS Result)	2.59
2	Immediate Settlement (Is 8009-1-1976)	3.18
3	Mohr-Coulomb soil model (ANSYS Result)	2.64

The results obtained from the ANSYS Software is observed as the 2.64 mm for mohr-coulomb soil model, 2.59mm for elastic soil model and the result obtained from immediate settlement concept 3.18 mm. Comparing all the results, outputs resemble nearabout. There is variation in settlement because we cannot replicate the complete ground condition on the software and the mohr-coulomb soil model shows more settlement because of the more soil parameters are used for the analysis. Hence, validation results are satisfactory.

Results of Soil-Structure interaction analysis

In the present study soil-structure analysis of G+3 RC building is done using the Mohr-Coulomb soil model in ANSYS R1 2022. The objectives of the work are soil-structure analysis of RC buildings, interaction is observed by comparing the flexible base building model with the same building with a fixed base. Different parameters of the buildings are observed and the effect of soil-structure interaction is analyzed. The parameters considered are vertical reactions, horizontal reactions and bending moments at footing level considering the Mohr-Coulomb model with varying types of soil.

Effect of SSI on Vertical Reaction (kN)

Footing Location	Fixed Base a	Hard Soil b	Medium Soil c	Soft Soil d	Ratio		
					b/a	c/a	d/a
Corner	674.00	693.30	736.17	760.80	1.03	1.09	1.13
Edge	1047.60	1078.80	1105.60	1121.30	1.03	1.06	1.07
Central	1568.90	1527.40	1481.10	1449.50	0.97	0.94	0.92

The parameter considered for the soil-structure interaction analysis are vertical reactions, horizontal reactions and bending moments at the footing level are compared to the flexible and fixed base model. As the above table suggests that the vertical reactions at footing level for hard soil shows 3% increment for corner and edge footing, while 3% decrement for the central footing due to the adjustments of the forces in the building. For medium soil 9% increments at the corner, 6% increments at the edge and a 6% decrement at the central footing. The loose soil shows some considerable effects 13% increment, 7% increment and 8% decrement at the corner, edge and central footing respectively

Effect of SSI on Horizontal Reaction (kN)

Footing Location	Fixed Base a	Hard Soil b	Medium Soil c	Soft Soil d	Ratio		
					b/a	c/a	d/a
Corner	21.30	21.20	25.20	32.09	1.00	1.18	1.51
Edge	17.82	23.66	29.62	37.52	1.33	1.66	2.11
Central	2.25	7.03	11.97	16.86	3.12	5.32	7.49

As the vertical reactions decrease at the central footing, the effect of SSI on horizontal reaction increases from corner footing to edge and contracting. Similarly, tabulated results suggest that there is a greater variation from hard soil to soft soil. Central footing shows considerable impact as it varies from 312% to 749% from hard soil to soft soil respectively. Unlike vertical reactions, horizontal reactions show greater variations.

Effect of SSI on Bending Moment (kN-m)

Footing Location	Fixed Base a	Hard Soil b	Medium Soil c	Soft Soil d	Ratio		
					b/a	c/a	d/a
Corner	24.39	26.62	32.47	43.67	1.09	1.33	1.79
Edge	21.80	32.92	43.28	56.26	1.51	1.99	2.58
Central	2.51	12.48	19.52	26.56	4.97	7.77	10.58

The bending moment value is increasing as the soil stiffness decreases. The soil-structure interaction effect also increases as the bending moment increases and the soil stiffness decreases. The soil with lesser stiffness shows more liability to the soil-structure effect. The tabulated data explains the variation of bending moment with respect to locations as well as for the different types of soil as soil changes from hard to soft soil. To study soil-structure interaction effect on bending moment ratio is generated by fixing the fixed base model as denominator and flexible base model for the different types of soil as the numerator. Here the ratio gives the idea about the impact of SSI on the bending moment concerning the footing and the varying soil types. For the corner footing for soft soil, the ratio is 1.79 times fixed base while for central footing it is 10.58 times fixed base. the effect of SSI on bending moment is more prevalent in soft soil and less in hard soil.

Conclusion

A G+3 RC framed building is considered for the SSI analysis using the ANSYS 2022R1 for varying types of C-ϕ soils. The soils are hard soil, medium soil, and soft soil. The building is analysed with help of various models, for the fixed base model and flexible soil models for three types of soil for the Mohr-Coulomb model. The focused parameters are the vertical forces, horizontal forces and bending moment at foundation level. The tabulated variation of each parameter is shown in the below table.

Effect of SSI on foundation reactions with varying soil types (Hard to Soft).

S.No.	Parameters	Effect of SSI Ratio (SSI/fixed)		
		Corner footing	Edge footing	Central footing
1	Vertical Reaction	1.03 to 1.13	1.03 to 1.07	0.97 to 0.92
2	Horizontal reaction	1.0 to 1.51	1.33 to 2.11	5.32 to 7.49
3	Bending Moment	1.09 to 1.79	1.51 to 2.58	4.97 to 10.58

1. The variation of the vertical reaction is 1.03 to 1.13 with respect to the varying soil as hard to the soft state. As the soil softens from hard soil to soft soil vertical reaction at the corner and the edge footings increases and SSI effect also increases. For the central footing vertical reaction reduces with the hard to soft soil variation due to reaction shifts towards the outer footings.

2. The variation of horizontal reaction at the footing is observed as 5.32 to 7.49 for the varying soil as hard to soft soil. The values suggest that the effect of SSI on the horizontal reaction increases with the change of soil from hard, medium to soft soil at all three locations.

3. For the Mohr-Coulomb soil model the variation of bending moment at the footing is observed as 4.97 to 10.58 for the varying soil as hard to soft soil.

4. The overall study says that soft soil is liable to fail compared to hard soil. A study of SSI is much more important for the soft soil for any multi floor structure.

5. The intensity of the vertical reaction is greater at central footing, but the SSI impact is more on the outer footing such as edge and corner footing.

6. The horizontal reaction and the bending moment shows greater effect on central footing, and minimum at corner footing.

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