International Journal Of Advance Research, Ideas And Innovations In Technology

ISSN: 2454-132X
Impact factor: 4.295
(Volume 3, Issue 6)
Available online at www.ijariit.com

Influence of Stratified Soil on Seismic Response of Pile Supported Building

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Abstract*: In the last few decades, it has been perceived that Soil Structure Interaction (SSI) changed the reaction attributes of a structural system due to huge and firm nature of structure and frequently, soil softness. In the current study, to depict the influence of soil structure interaction on the seismic response of a structure due to earthquake loading, a 5 storied (G+4) simple square building supported on pile foundation resting on stratified soil was selected. The building sections were modelled and analysed for different configurations (i.e., with and without slab and infill) using finite element method SAP2000. The deformations under seismic loading in the structure and piles by incorporating the effect of soil-structure interaction and fixed base condition were extracted, compared and discussed. Impact of variety of the parameters on different soil conditions like variation in soil profile and number of soil layers, influence of slab and infill are considered for which the buildings are modelled by alternate approaches, namely, (1) bare frame with fixed supports, (2) frames including slab and infill with support accounting for soil-flexibility. The results indicate that the roof displacement varies significantly for different soil layer combinations if included the soil structure interaction compared to that of fixed base analysis. Thus considering the effect of SSI is essential. The horizontal displacement of the structure is maximum for a bare frame with slab when compared to bare frame and infill frame. When infill wall is added to the structure, the horizontal displacement is decreased due to the stiffness of the infill wall.

***Keywords:* Soil Structure Interaction, RC Square Frames, Natural Period, Lateral Deflection, Soil Displacement, Static Analysis, Time History Analysis.**

I. INTRODUCTION

Civil engineering structures involve structural elements with direct contact with the ground. When the external actions, such as earthquakes, act on these systems, neither the structural displacements nor the ground displacements, are independent of each other. The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction (SSI) [1]. The response of structure relies upon on the properties of soil, structure and the way of the excitation. Implementing soil-structure interaction impacts empowers the designer to assess real displacements of the soil-foundation structure framework precisely under the influence of seismic action. Present design practice for dynamic loading assumes the building to be fixed at their bases. But in reality, supporting soil medium permits movement to some degree because of their common capacity to deform which diminish the overall lateral stiffness of the structural system resulting in a lengthening of lateral natural time periods. This, in turn, effects the response of the building considerably.

Depending on the amount of load and nature of supporting sub soil, type of the foundation is chosen for the building. Generally, the multi-storied buildings constructed on weak strata at shallow depth are supported on a pile foundation.

PILES are a particular type of foundation inserted deep into the ground. Essentially, they are long, slender members that transfer the load of the superstructure to greater depths. The piles transfer the load of the superstructure through two ways: (a) Shear generated along the surface of the pile due to soil–pile friction; (b) Point resistance due to the bearing of the pile at its bottom [2].

At present Soil Structure Interaction is a standout amongst the most thriving zones of exploration in Structural Engineering. It can be characterized as the coupling between structures

And it's supporting medium (bedrock or soil bed) during an earthquake. Tackling such problems has become possible lately due to a revolution in computer technology. Works done in the late decade have demonstrated the significance of structure-soil-structure interaction on the dynamic response of key structures such as silos, storage tanks, and offshore structures. Hence SSI calls for improvement in Codal provisions for the seismic design and communications between geotechnical and structural engineers.

Compared with the counterpart fixed-base system, SSI has two basic effects on structural response. Firstly, the SSI system has an increased number of degrees of freedom and thus modified dynamic characteristics. Secondly, a significant part of the vibration energy of the SSI system may be dissipated either by radiation waves, emanating from the vibrating foundation–structure system back into the soil, or by hysteretic material damping in the soil. The result is that SSI systems have longer natural periods of vibration than their fixed-base counterparts [3].

In the current study, to depict the influence of soil structure interaction on the seismic response of a structure due to earthquake loading, a 5 storied (G+4) simple square building supported on pile foundation resting on stratified soil was selected. The building sections were modelled and analysed for different configurations (i.e., with and without slab and infill) using finite element method SAP2000 subjected to Bhuj earthquake ground motion in the time domain. The deformations under seismic loading in the structure and piles by incorporating the effect of soil-structure interaction and fixed base condition were extracted, compared and discussed. Impact of variety of the parameters on different soil conditions like variation in soil profile and number of soil layers, influence of slab and infill are considered for which the buildings are modelled by alternate approaches, namely, (1) bare frame with fixed supports, (2) frames including slab and infill with support accounting for soil-flexibility. Variations in the natural period are noted down for both support conditions and a comparative study has been done.

II. IDEALIZATION OF THE SYSTEM

2.1Structural Idealization

To study the seismic soil structure interaction, three buildings with the same dimension but with the inclusion of elements i.e., bare frame, frame with slab and frame with slab and infill were modelled using SAP2000 software. 3D models of the simple square frame with the single bay in both X and Y directions were modelled. The storey height and bay width of all building frames were chosen as 3m and 5m respectively, which is appropriate for a residential building. The thickness of floor slab, roof and infill were taken as 130mm, 130mm and 230 respectively. Beam and Column dimensions were as tabulated in table 1. The grid dimensions and pile dimensions were calculated based on the axial load carrying capacity. Square Pile is of 500mm side dimension and 6m long, and the pile cap with cross section 500x500mm having length 2500mm. The materials considered for the design were M20 grade concrete and Fe 415 steel.

TABLE 1
DETAILS OF THE BUILDING FRAME, SOIL MODEL, AND PILE

Soil Model	Width = 30m Depth = 18m Length = 30m
Concrete Frame	Columns = 0.3m X 0.3m Beams = 0.3m X 0.3m
Infill	Height = 2.7m Width = 4.7m Thickness = 0.23m
Concrete Piles	Length of piles = 6m Cross section = 0.5m x 0.5m
Concrete Pile caps	Length = 2.5m Cross section = 0.5m x 0.5m
Pile Groups	2 x 1 piles of spacing 0.5m
Storey Height	3m
Number of Bays	1 bay x 1bay
Bay Width	5m

2.2 Idealization of Soil

The structures were assumed to be resting on four different types of soil with varying soil profile and depth and analysed on two layers and three layers. The soil was assumed to be linear, elastic, and isotropic in nature and discretised as a solid medium. Generally, the horizontal distance between soil boundaries is assumed to be five times the structural width. As the most amplification occurs within the first 30 m of the soil profile, which is in agreement with most of the modern seismic codes (e.g., ATC-40 1996, NEHRP 2003), these boundaries do not absorb energy but for the reduction of reflexive wave's effects, the distance between the structure and boundaries are increased. [4]

The soil dimension considered is 30 x 30 m in both X and Y direction and 18m in the Z direction. The soil boundary limit conditions have been postulated as zero displacements. The structures were analysed for four different soil combination conditions and then compared with the fixed base condition. The properties of loose sand and very soft clay considered for the analysis are as given in Table 2.

TABLE 2
DETAILS OF SOIL PARAMETERS CONSIDERED

Soil Type	**Unsaturated Unit Weight (Γunsat)**	**Young's Modulus (Es)**	**Poisson's Ratio (μ)**
Loose Sand	18.5 kN/m^3	24x 10^3 kN/m^2	0.3
Very Soft Clay	18 kN/m^3	15x 10^3 kN/m^2	0.4

III. METHODOLOGY

Both static and transient analysis of bare frame, frame with slab and infill structures were:
Performed for fixed base condition and soil structure interaction models for all four combinations of soils on both loose sand and very soft clay conditions to examine the earthquake response of the Structures. A transient analysis was done with the time history data of Bhuj earthquake ground motion. The earthquake response of the building frames considering the flexibility of the soil is examined and the results are compared with the fixed base condition. The analysis was carried out to find the displacement, natural frequencies and corresponding natural period of the structures.
The effect of soil structure interaction on the building frames for the entire study is carried out using Bhuj earthquake (2001) data with peak acceleration 1.0382 m/s^2. The Acceleration-time history of Bhuj earthquake ground motion is as shown in figure 2.

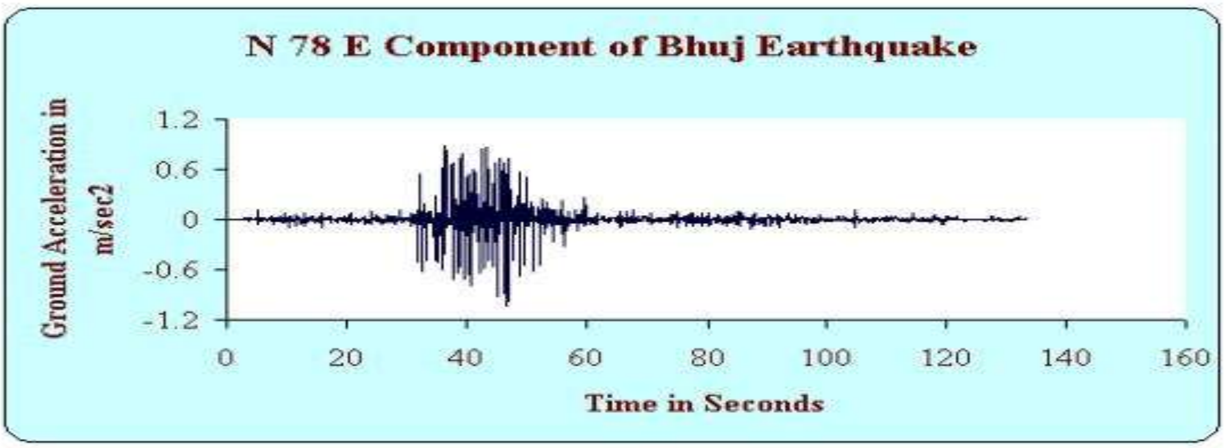

Fig. 2: Acceleration Time History of Bhuj Earthquake Ground Motion with Acceleration of 1.0382 g

IV RESULTS AND DISCUSIONS

All three models of structures assumed to be resting on four combinations of soil layers is investigated for the real earthquake excitations. The following section shows the changes in horizontal displacement, acceleration, bending moment and shear force accounting the effect of soil-structure interaction. The shear force and bending moment of the structure were observed only along the length of the pile.

The combinations of soil profiles considered in analysis are as mentioned below:

- Combination 1 (C1) - 9m clay + 9m sand
- Combination 2(C2) - 4m clay + 14m sand
- Combination 3(C3) - 6m clay + 6m sand + 6m clay
- Combination 4(C4) - 6m sand + 6m clay + 6m sand

4.1 Roof Displacement

Variation in roof displacement due to earthquake excitation for different configuration of the structure with different types of soils has been studied. The values of roof displacement and its percentage variations considering the effect of SSI are tabulated Table 3.

4.1.1 Combination 1(C1) - 9m clay + 9m sand

TABLE 4.1
VALUES OF DISPLACEMENTS (MM)

Storey Level	Type of Structure	Dynamic Analysis	
		Fixed Base	(SSI)
Top Storey	Bare Frame	2.31	18.85
	Bare Frame with Slab	3.75	20.32
	Infill Frame	1.13	10.35

The results show that roof displacement values are more in dynamic analysis than fixed base Analysis

4.1.2 Combination 2(C2) - 4m clay + 14 sand

TABLE 4.2
VALUES OF DISPLACEMENTS (MM)

Storey Level	Type of Structure	Dynamic Analysis	
		Fixed base	(SSI)
Top Storey	Bare Frame	2.31	17.87
	Bare Frame with Slab	3.75	29.15
	Infill Frame	1.13	11.85

4.1.3 Combination 3(C3) - 6m clay + 6m sand + 6m clay

TABLE 4.3
VALUES OF DISPLACEMENTS (MM)

Storey Level	Type of Structure	Dynamic Analysis	
		Fixed Base	(SSI)
Top Storey	Bare Frame	2.31	15.6
	Bare Frame with Slab	3.75	21.93
	Infill Frame	1.13	12.92

4.1.4 Combination 4(C4) - 6m sand + 6m clay + 6m sand

TABLE 4.4
VALUES OF DISPLACEMENTS (MM)

Storey Level	Type of Structure	Dynamic Analysis	
		Fixed Base	(SSI)
Top Storey	Bare Frame	2.31	13.37
	Bare Frame with Slab	3.75	16.77
	Infill Frame	1.13	9.97

4.2. Horizontal Displacement of Bare Frame

TABLE 4.5
HORIZONTAL DISPLACEMENT V/S DEPTH AT DIFFERENT LEVELS FOR ALL THE SOIL MODELS

Levels	Storey Height (m)	Horizontal Displacement (mm)			
		Combination 1	Combination 2	Combination 3	Combination 4
Storey 5	15	18.85	17.87	15.6	13.37
Storey 4	12	17.63	16.6	14.4	12.37
Storey 3	9	15.85	14.72	12.8	11.04
Storey 2	6	13.56	12.29	11.08	9.4
Storey 1	3	11.01	10.17	9.2	7.6
Pile Head	0	8.77	8.49	7.8	6.3

At 1m Below	-1	8.25	7.9	7.4	6.08
At 2m Below	-2	7.82	7.5	7.1	5.82
At 3m Below	-3	7.39	7.2	6.8	5.62
At 4m Below	-4	6.95	6.8	6.5	5.41
At 5m Below	-5	6.52	6.4	6.2	5.21
Tip of the Pile	-6	6.09	6.1	5.9	5.01

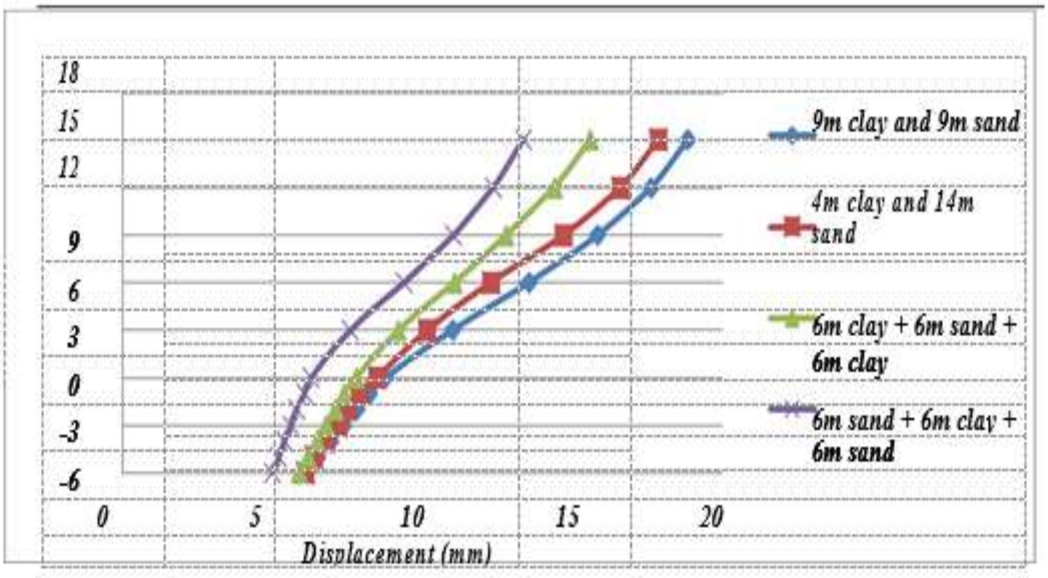

Fig. 3: Horizontal Displacement v/s Depth at Different Levels

Figure 3 shows the horizontal displacement of the bare frame at different levels for all four combinations of soil. From above, it is observed that displacement of the structure is maximum for Combination 1 when compared to rest of the soil combinations. The displacement of pile below the ground is also more for Combination 1 i.e., for - 9m clay + 9m sand.

4.3 Horizontal Displacement of Bare Frame with Slab

TABLE 4.6
HORIZONTAL DISPLACEMENT V/S DEPTH AT DIFFERENT LEVELS FOR ALL THE SOIL MODELS

Levels	STOREY Height (m)	Horizontal Displacement (mm)			
		Combination 1	Combination 2	Combination 3	Combination 4
Storey 5	15	20.32	29.15	21.93	16.77
Storey 4	12	18.62	26.58	19.64	15.01
Storey 3	9	16.15	22.62	16.09	12.24

Storey 2	6	13.04	17.52	11.53	9.47
Storey 1	3	9.62	11.82	7.22	7.30
Pile Head	0	6.80	8.29	7.63	5.77
At 1m Below	-1	6.33	7.85	7.33	5.63
At 2m Below	-2	5.96	7.50	7.11	5.48
At 3m Below	-3	5.58	7.14	6.88	5.32
At 4m Below	-4	5.20	6.75	6.64	5.16
At 5m Below	-5	4.83	6.41	6.39	4.99
Tip of the Pile	-6	4.48	6.06	6.11	4.82

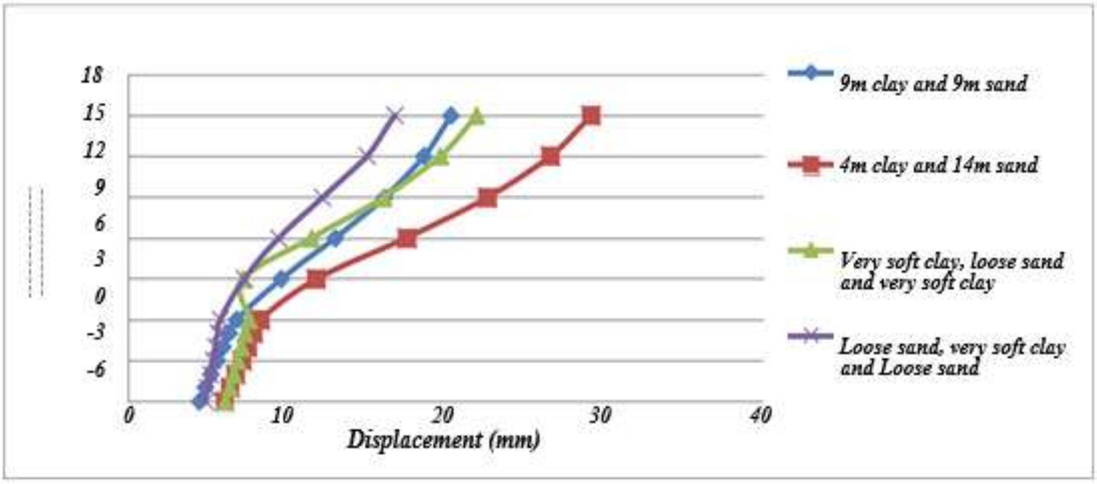

Fig. 4: Horizontal Displacement v/s Depth at Different Levels for all the Soil Models

Figure 4 shows the horizontal displacement of the bare frame with a slab at different levels for above combination of soil. From above values, it is clear that the displacement of the structure is maximum for Combination 2 when compared above the ground level. The displacement of pile below the ground is also more for Combination 2 i.e., C2 - 4m clay + 14 sand.

4.4. Horizontal Displacement of Infill Frame

TABLE 4.7
HORIZONTAL DISPLACEMENT V/S DEPTH AT DIFFERENT LEVELS FOR ALL THE SOIL MODELS

Levels	Storey Height (m)	Horizontal Displacement (mm)			
		Combination 1	Combination 2	Combination 3	Combination 4
Storey 5	15	10.35	11.85	12.92	9.97
Storey 4	12	9.67	10.93	11.88	9.14
Storey 3	9	8.98	10.24	10.85	8.33
Storey 2	6	8.29	9.67	9.85	7.55
Storey 1	3	7.60	9.16	8.93	6.82
Pile Head	0	6.92	8.69	8.12	6.17
At 1m Below	-1	6.199	8.11	7.49	5.76
At 2m Below	-2	5.88	7.78	7.17	5.56
At 3m Below	-3	5.55	7.43	6.85	5.36
At 4m Below	-4	5.23	7.07	6.54	5.16
At 5m Below	-5	4.91	6.75	6.23	4.97
Tip of the Pile	-6	4.62	6.44	5.94	4.80

Fig. 5: Horizontal Displacement v/s Depth at Different Levels for all the Soil Models

Figure 5 shows the horizontal displacement of infill frame at different levels for all the soil models considered. The horizontal displacement of the structure is maximum for Combination 3 when compared to all other soil models above the ground level. The displacement of pile below the ground is more for Combination 2 when compared to all other soil models.

4.5. Acceleration Response of Top Floor

Dynamic analysis is carried out to find the response of the different configuration of the structure with different properties of soils. In order to detail the bare frame, bare frame with slab and infill frame effects, the top floor response of the different configuration of the structure with different types of soils is plotted as shown in fig 6,7,8,9.

From the figure, it has been observed that increase in response for a bare frame with slab when compared to bare frame and infill frame. To understand the behaviour in detail a study has been carried out for four soil combinations with a modulus of elasticity ranging from 15000 kN/m^2 to 80000 kN/m^2. For an understanding on the response of the structure for different properties of soils are plotted. The acceleration response of structure for combination 3 (i.e. 6m clay + 6m sand + 6m clay) is more when compared to acceleration response of structure for other soil models.

4.5.1 Combination 1(C1) - 9m clay + 9m Sand

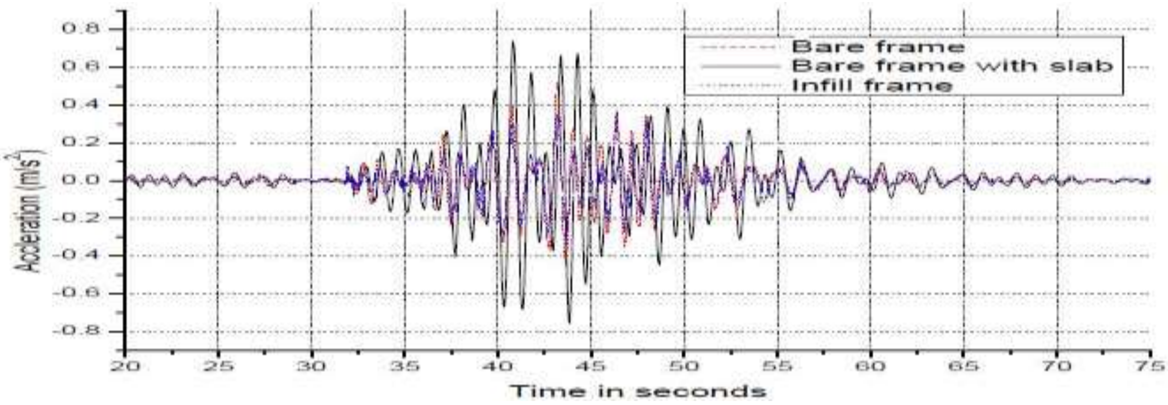

Fig. 6: Acceleration Response of Top Floor for Bare Frame, Bare Frame with Slab and Infill Frame under Bhuj Earthquake

4.5.2 Combination 2(C2) - 4m clay + 14 sand

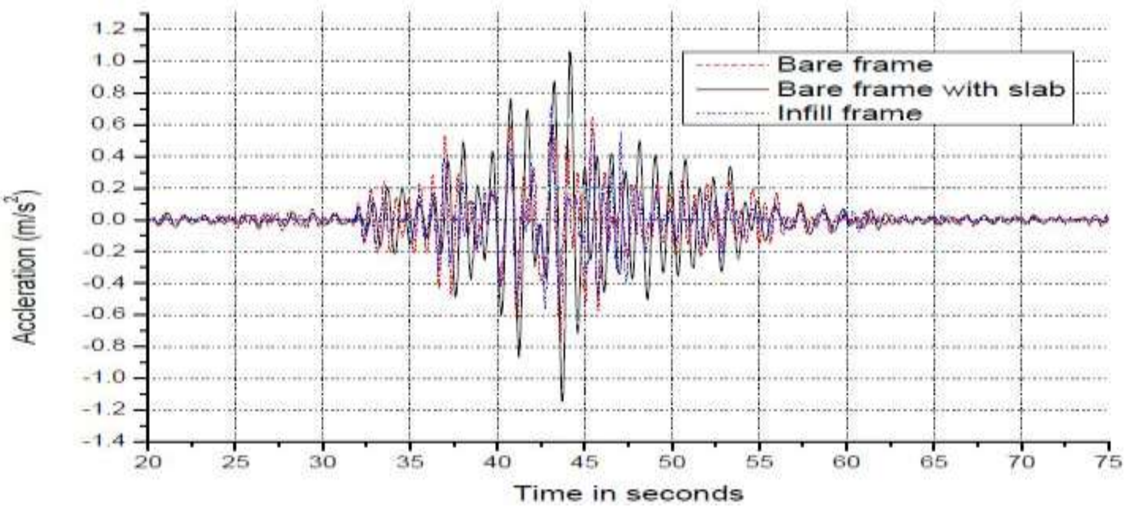

Fig. 7: Acceleration Response of Top Floor for Bare Frame, Bare Frame with Slab and Infill Frame under Bhuj Earthquake

4.5.3 Combination 3(C3) - 6m clay + 6m sand + 6m clay

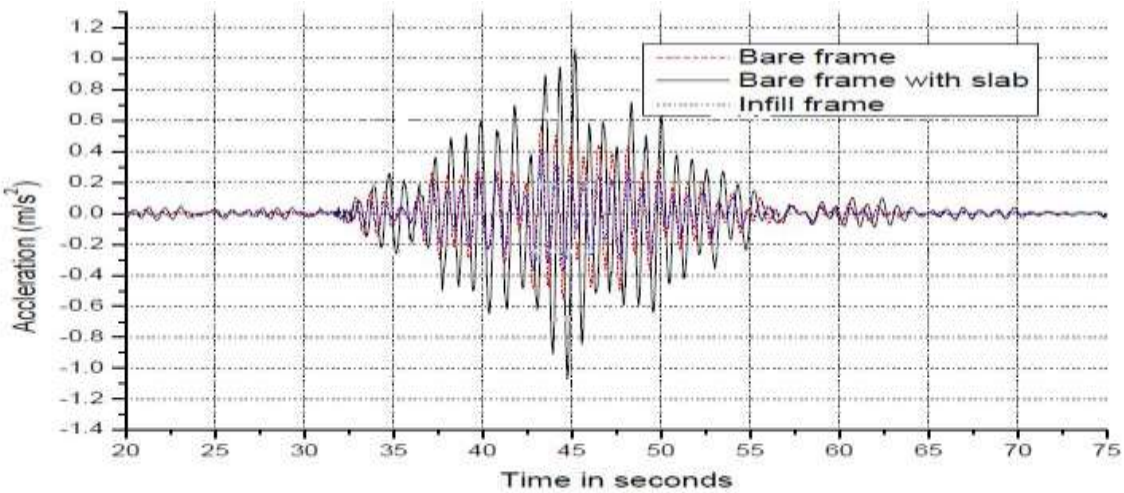

Fig. 8: Acceleration Response of Top Floor for Bare Frame, Bare Frame with Slab and Infill Frame under Bhuj Earthquake

4.5.4 Combination 4(C4) - 6m sand + 6m clay + 6m sand

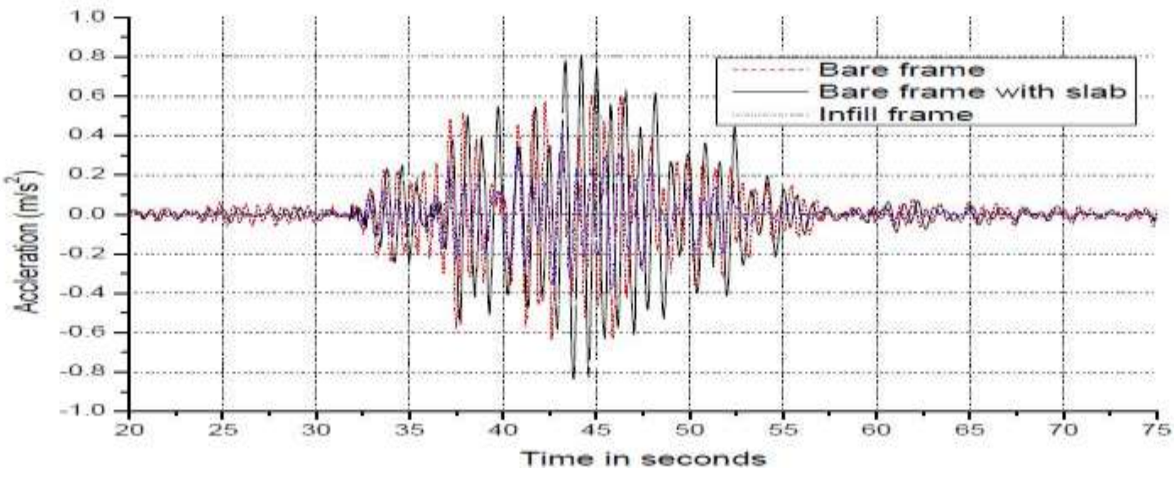

Fig. 9: Acceleration Response of Top Floor for Bare Frame, Bare Frame with Slab and Infill Frame under Bhuj Earthquake

V. CONCLUSIONS

1. The roof displacement varies significantly for different soil layer combinations if included the effect of soil-structure interaction. Displacement is less for the fixed condition and increases when SSI is taken into consideration.
2. The horizontal displacement of the structure is maximum for combination 1(i.e. 9m clay + 9m sand) layer when compared with all other soil combination above the ground level.
3. The horizontal displacement of the structure is maximum for a bare frame with slab when compared to bare frame and infill frame. When infill wall is added to the structure, the horizontal displacement is decreased due to the stiffness of the infill wall.
4. The acceleration response of top floor has been reduced for infill frame when compared to the bare frame and bare frame with the slab.
5. There is a reduction in acceleration response of structure for very soft clay when compared to acceleration response of structure for loose sand and dense sand.

ACKNOWLEDGMENT

We sincerely acknowledge the support offered by the Management, CEO, Principal, HOD and Faculty of Civil Engineering Department-MSRIT, Bengaluru, Karnataka, India.

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