Analysis of R.C. building frame with raft foundation considering soil structure interaction

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Abstract – *Civil engineering structures such as building must have sufficient safety margin under dynamic loading like earthquake. The dynamic performance of a RCC building can be determined accurately that requires appropriate modelling considering foundation-soil, building-foundation and soil interactions. Building-foundation-soil interactions are complex phenomena requiring advanced mathematical and numerical modelling. The soil-structure interaction plays an important role particularly when subjected to seismic excitation, due to the potentially disastrous consequences of a seismic event. In the present work effectiveness of modelling in software for determination of seismic behavior of the medium rise building over raft considering soil flexibility interaction is studied. Modal analysis of building system is carried out in software. For the analysis, three dimensional multiple bays regular RC building model for eight storeys is considered and the soil beneath the structure is modelled as equivalent soil springs connected to the raft foundation. The response spectrum analysis of the soil-structure model was carried out using the general software STAAD.Pro. In both the cases (fixed base and flexible base) of modelling the structure, the earthquake records have been scaled according to the Indian Standard 1893-2002 for each type of soil (i.e. I, II & III) and applied to the ordinary moment resisting frame with seismic zone III, zone IV and zone V.*

Key Words: Dynamic soil-structure interaction, Seismic response, STAAD.Pro, Natural period, Spring stiffness, Displacement, Mat foundation.

1. INTRODUCTION

Earlier structures and foundations were dealt in complete isolation, where the structural and geo-technical/foundation engineers hardly interacted. While the structural engineer was only bothered about the structural configuration of the system in hand he hardly cared to know anything more about soil other than the allowable bearing capacity and its generic nature, provided of course the foundation design is within his scope of work. On the other hand the geotechnical engineer only remained focused on the inherent soil characteristics like (c, φ, Nc, Nq, Nγ, eo, Cc, G etc.) and recommending the type of foundation (like isolated footing, raft, pile etc.) or at best sizing and designing the same. The crux of this scenario was that nobody got the overall picture, while in reality under static or dynamic loading the foundation and the structure do behave in tandem.

The common design practice for dynamic loading assumes the building frames to be fixed at their bases. In reality, supporting soil medium allows movement to some extent due to its natural ability to deform. This may decrease the overall stiffness of the structural system and hence, may increase the natural periods of the system. Such influence of partial fixity of structures at the foundation level due to soil-flexibility in turn alters the response. On the other hand, the extent of fixity offered by soil at the base of the structure depends on the load transferred from the structure to the soil as the same decides the type and size of foundation to be provided. Such an interdependent behaviour between soil and structure regulating the overall response is referred to as soil structure interaction.

2. LITERATURE REVIEW

Bhojegowda V T and K G Subramanya (2015): Present study provides systematic guidelines for determining the natural periods of framed buildings due to the effect of soil-flexibility and identification of spring stiffness for different regular and irregular story buildings and various influential parameters are identified. The study were carried out for building with isolated, mat and pile foundations for soft, medium and hard soil conditions. It is observed that framed structure with pile foundation resting on hard, medium and soft soil can be treated as fixed since no much variation in the response of the structure. Famed structure with mat foundation possesses high foundation stiffness than isolated foundation hence base shear for mat foundation has increased and other parameters like displacement, bending moment and time period were reduced.

F. Behnamfar, M. Banizadeh (2016): The authors established nonlinear dynamic response of buildings on two different soft soils including soil–structure interaction. For each building on each soil type a suit of 10 consistent earth-quake motions were considered and scaled through a rational procedure. Responses of buildings including maximum base shear, story drift, and plastic hinge rotation were calculated. The rotations of plastic hinges of beams and columns of each story were calculated as absolute values of maximum rotations at each point averaged between the 10 associated earthquakes. RCC buildings being 3, 5, 6, 8, 9 stories high, resting on soft and very soft soil types, once with moment resisting and once with concrete shear walls are considered. The analysis is done for both fixed-based and flexible-base buildings. The results show that for a flexible base, the location of maximum drift shifts to the first story where the most intensive vulnerability is observed SSI changes the pattern of distribution of vulnerability especially for the beams of shear wall buildings and intensifies the seismic vulnerability on soft soils. Author concluded that soil structure interaction worsens the performance level of structural members of the lower stories of moment frame and shear wall buildings.

Hany Farouk and Mohamed Farouk (2016): In this paper soil, foundation, and superstructure interaction for plane two-bay frames were studied. Effect of the superstructure rigidity on the damping of differential settlement in consideration to the redistribution of loads was investigated. The results of five model groups with 54 frames were collected and studied for each group. It is observed from investigation that no impact of footing rigidity on the average contact stress under the footings or on the maximum settlement but superstructure rigidity having a significant effect on the redistribution loads between the inner and outer walls. Analyses charts and new equations are prepared from the results of the modeled frames to calculate the average contact stress and maximum settlements under the inner and outer footings for plane 2-bay frames.

3. METHODOLOGY

3.1 Idealization of building and raft foundations

To analyze the dynamic behaviour while considering the effect of soil flexibility, building frames have been idealized as 3-D space frames using two nodded frame elements and have being analyzed using STAAD.Pro software. In conventional design technique, the building is analyzed as fixed base frame with the help of computer software. In present study considers frames to see how correctly the influence of soil-structure Interaction on dynamic behavior can be predicated. This may give an idea about the error, which one should liable to commit if this popular but grossly inaccurate approach is invoked.

3.2 Idealization of soil

The function of the foundation media is to resist the forces applied to it by the base of the buildings. During earthquake, a rigid base may be subjected to displacement in six degrees of freedom, and the resistance of soil may be expressed by the six corresponding resultant force component. Hence the structural behavior of the elastic half space is represented completely by a set of force displacement relationships defined for these degrees of freedom. To simulate the static behavior of soil-structure system, it is evident that the foundation medium could be modeled by six linear springs acting in rigid base degrees of freedom. Appropriate static spring constants can be evaluated for the elastic half space by the method of continuum mechanics.

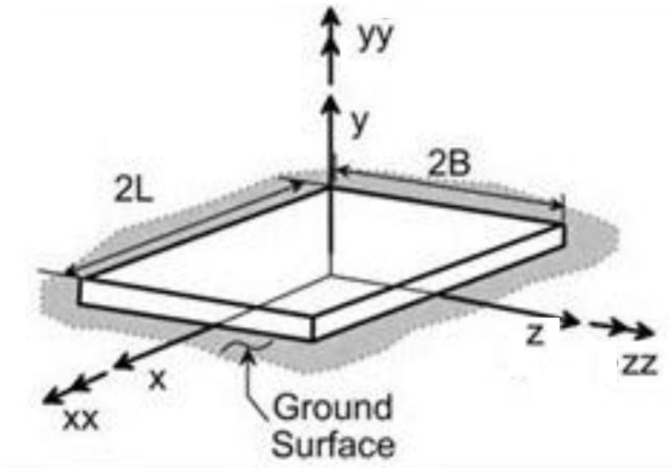

Fig -1: Equivalent soil spring stiffness

To analyze the entire structural system consisting of soil-foundation and structure under dynamic loading, the impendence function associated with a rigid mass less foundation may be used to make the analysis most general, translations of foundations in two mutually perpendicular principal horizontal directions and vertical direction as well as rotations of the same about these 3 directions are considered in the present study. The mat foundations system is idealized has a combination of a series of parallel foundations strips oriented in two principal directions resting in the same horizontal plane. Springs are attached in the above mentioned six degrees of freedom. The effect of soil-flexibility on building resting on different types of soils (hard, medium, soft) is also attempted to be studied in the present work.

Table -1: Stiffnesses of equivalent soil springs along various degrees of freedom [14]

Degrees of freedom	Stiffness of equivalent soil spring
Translation along x – axis (Kx)	KZ -{[(0.2GL)/(0.75-μ)][1-(B/L)}
Translation along y – axis (Ky)	$\{[(2GL)/(1-\mu)][0.73+1.54(B/L)^{0.75}]\}$
Translation along z – axis (Kz)	$\{[(2GL)/(2-\mu)][2+2.5(B/L)^{0.85}]\}$
Rocking about x – axis (Krx)	$\{[(GI_X^{0.75})/(1-\mu)](L/B)^{0.25}[2.4+0.5(B/L)]\}$
Torsion along y – axis (Kry)	$GJ_t^{0.75}\{4+11[1-(B/L)]^{10}\}$
Rocking about z – axis (Krz)	$\{[(GI_Z^{0.75})/(1-\mu)][3(L/B)^{0.15}]\}$

Gross spring values is obtained on the full raft dimension as mentioned in table 1 and then are broken up into discrete values.

$$K' = K\,(A_P/A_G)$$

Where:
K' - Value of discrete spring for the finite element

K - Value of gross spring considering the overall dimension of the raft
A_P - Area of the finite element plate
A_G - Gross area of the raft

4. MODELING AND ANALYSIS

4.1 Details of soil parameters considered

The structure are assumed to be resting on three different soil (soft, medium and hard). The details of soils considered for present study is shown in table 2.

Table -2: Characteristic properties of soils [9]

Type of soil	Shear wave velocity Vs (m/s)	Elastic modulus E (kg/cm²)	Shear modulus G (kg/cm²)	Density of soil ρ (kN/m³)	Poisson's ratio of soil μ
Hard	600	16400	6480	17.322	0.28
Medium	320	4945	1808	16.841	0.39
Soft	150	935	335	14.435	0.40

4.2 Superstructure

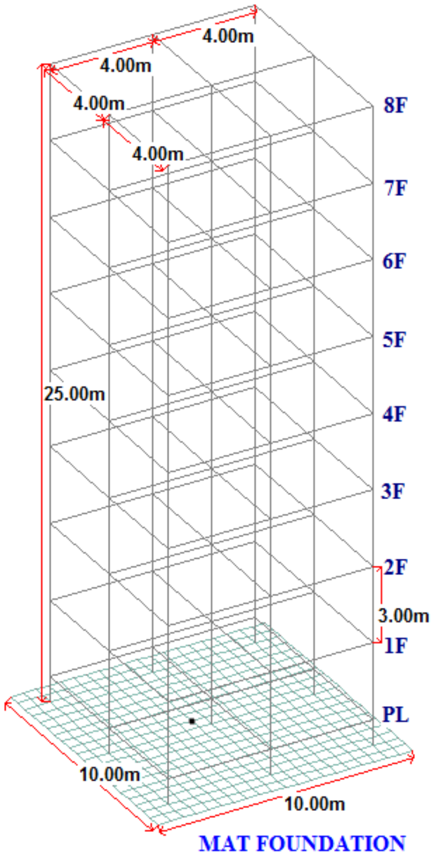

Fig -2: Bare Frame with mat footing

The influence of different soil conditions and different seismic zones on the dynamic behavior of building frame with mat foundation, with and without considering the effect of soil-structure interaction has also been studied. To look into such effect, 2 bay 8 storey building frame resting on mat foundation have been considered. Buildings with such configuration have been considered to include the possible representative cases or typical mid-rise buildings. The storey height of the building frame was chosen as 3m and the length of the building frame was chosen as 4m.

For all the cases, the dimensions of reinforced-concrete columns were taken 300mmx450mm, for beams the dimensions were taken as 230mmx450mm. Similarly, the thickness of the roof and floor slabs was taken as 150mm. These dimensions were arrived on the basis of the design following the respective Indian code for design of reinforced concrete structures. However, these design data are believed to be practicable and hence, do not affect the generality of the conclusions.

4.3 Foundation

Raft foundation of size 10m x 10m with 650mm thickness is considered for all structures. Depth of foundation is 1m for all the cases considered. Raft foundation is designed using SAFE software and it is observed that 650mm thickness of raft is satisfactory.

4.4 Analysis data

1) Live Load : 4.0 kN/m² at typical floor
 : 1.5 kN/m² on terrace
2) Floor finish : 1.0kN/m²
3) Earthquake Load : As per IS-1893(Part 1)-2002 using STAAD Program.
4) Depth of Foundation : 1 m
5) Storey Height : 3 m
6) Walls : 230 mm thick brick masonry wall
7) Compressive strength of Concrete (f_{ck}) : 20 N/mm²
8) Reinforcement (f_y) : 415 N/mm²
9) Poisson's ratio : 0.15

5. RESULTS AND DISCUSSIONS

The results are presented in the form of tables and graphs considering the effect of soil flexibility with that of the fixed base condition. The variation of natural period and structural response for various parameters like storey displacements, base shear, shear force, bending moment for structural element like raft, column & beams of the building models resting on different types of soil and seismic zones presented. The properties of the soil used for present study are given in tables 2. The trends observed in the results are also discussed in these sections.

5.1 Variation in natural period

The values of natural period are given in table 3. It is observed that there is no change in natural period for all seismic zones and soil types with fixed base condition. There is no effect of seismic zones on natural period. It is observed that as the soil flexibility increases the natural period increases.

Table -3: Natural period (Seconds)

Base		Fixed	Flexible
Zone III	Soft	1.398	1.673
	Medium	1.398	1.460
	Hard	1.398	1.423
Zone IV	Soft	1.398	1.673
	Medium	1.398	1.460
	Hard	1.398	1.423
Zone V	Soft	1.398	1.673
	Medium	1.398	1.460
	Hard	1.398	1.423

5.2 Variation in base shear

Variation in base shear due to different earthquake zone for building frame with different soil conditions has been studied. The values of base shear and its percentage variation are given in table 3. It is observed that for all seismic zones condition there is a substantial increase in base shear in soft and medium soils as compared to hard soil. A variation of 35.78% in comparison with hard soil is seen in base shear for medium soil and 66.77% for soft soil for building with fixed base condition is in seismic zone III.

Table -4: Values of base shear

Zone		III		IV		V	
Base		Fixed	Flexible	Fixed	Flexible	Fixed	Flexible
Values of base shear(kN)	Hard	313	304	468	457	703	685
	Medium	425	396	637	593	956	891
	Soft	522	404	783	606	1174	909
Percentage variation in	Medium	35.78	30.26	36.11	29.76	35.99	30.07
	Soft	66.77	32.89	67.31	32.60	67.00	32.70

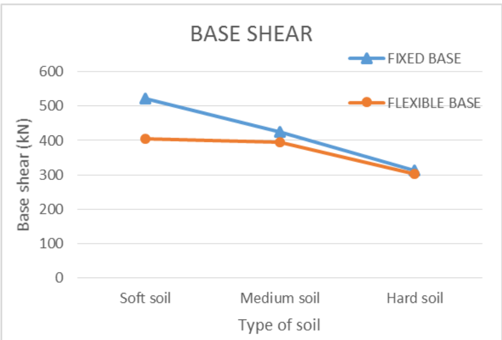

Chart -1: Variation of base shear with flexibility of soil for zone III

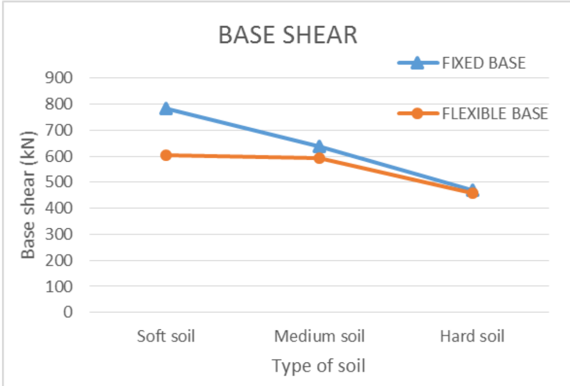

Chart -2: Variation of base shear with flexibility of soil for zone IV

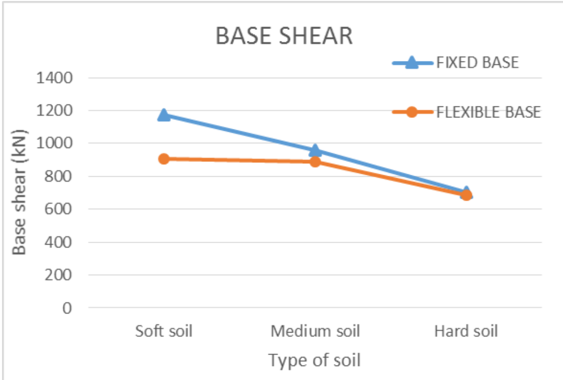

Chart -3: Variation of base shear with flexibility of soil for zone V

5.3 Variation of storey displacement

It is observed that for all seismic zones condition there is a substantial increase in storey displacement in soft and medium soils as compared to hard soil. A variation of 51.72%, 27.56% and 20.84% in comparison with fixed base and flexible base is seen for roof displacement in soft, medium and hard soil respectively for seismic zone III, zone IV and zone V.

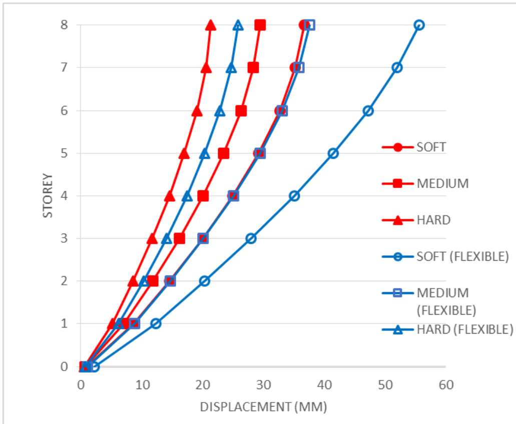

Chart -4: Variation of storey displacement with flexibility of soil for zone III

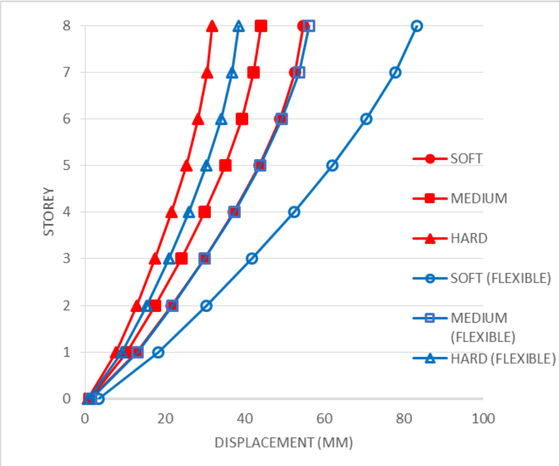

Chart -5: Variation of storey displacement with flexibility of soil for zone IV

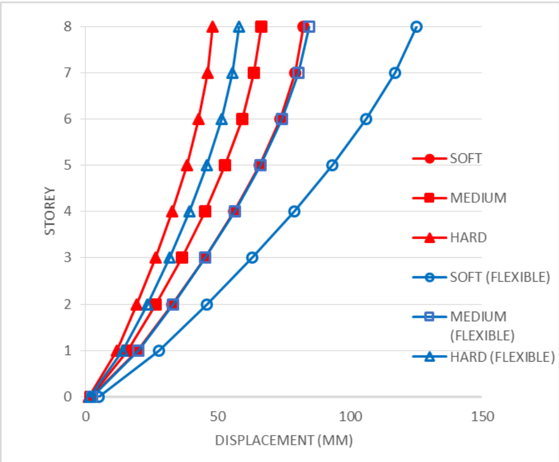

Chart -6: Variation of storey displacement with flexibility of soil for zone V

5.4 Variation in column axial force

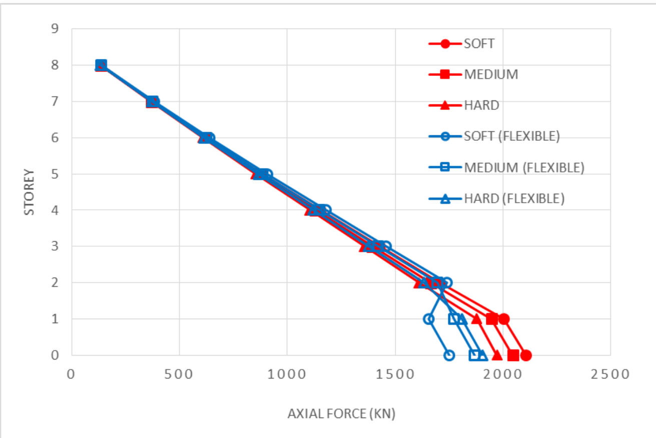

Chart -7: Variation of column axial forces with flexibility of soil for zone III

The maximum values of axial forces in column are plotted for different soil condition. A variation of axial forces in column are observed for 1.5(DL+LL)+1EQX loading condition. A reduction of 16.88%, 8.59% and 3.44% in comparison with fixed base and flexible base is seen in plinth level column axial force for soft, medium and hard soil respectively for seismic zone III.

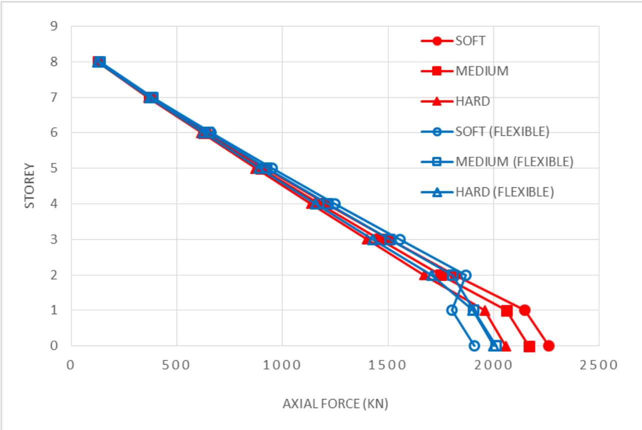

Chart -8: Variation of column axial forces with flexibility of soil for zone IV

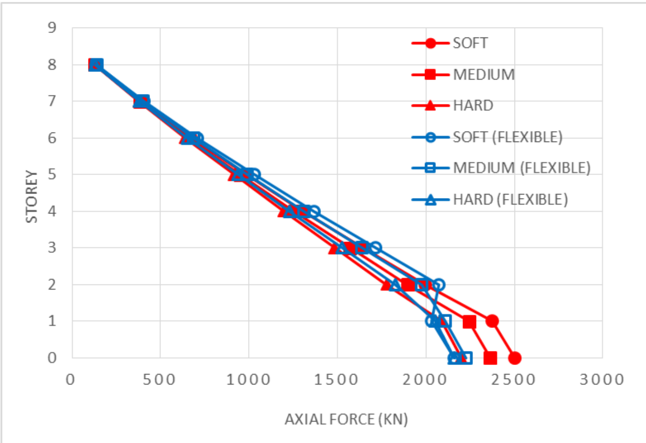

Chart -9: Variation of column axial forces with flexibility of soil for zone V

5.5 Variation in column shear force

A variation of axial forces in column are observed for 1.5(DL+LL)+1EQX loading condition. A reduction of 76.52%, 50.23% and 28.22% in comparison with fixed base and flexible base is seen in plinth level column axial force for soft, medium and hard soil respectively for seismic zone III. The seismic effect of zone III, zone IV and zone V on shear force in column is studied. It is found that the shear force in column is always higher for seismic zone V for both fixed base and flexible base condition.

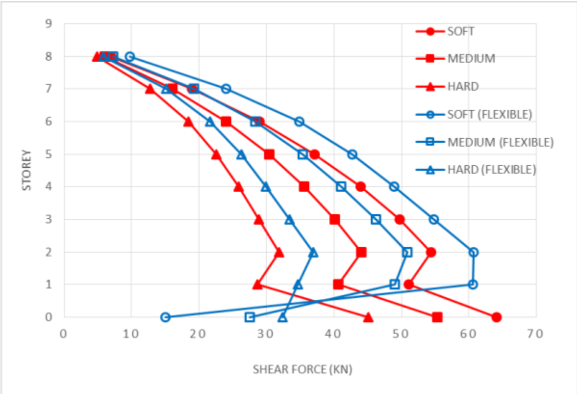

Chart -10: Variation of column shear forces with flexibility of soil for zone III

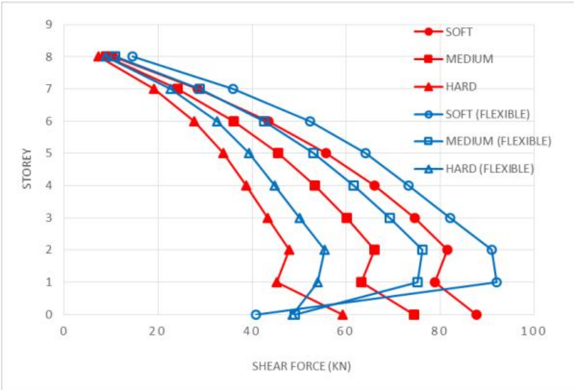

Chart -11: Variation of column shear forces with flexibility of soil for zone IV

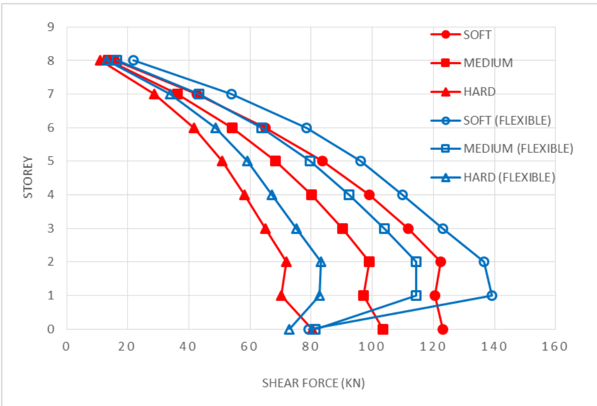

Chart -12: Variation of column shear forces with flexibility of soil for zone V

5.6 Variation in column bending moment

A variation of 40.07%, 21.76% and 18.83% in comparison with fixed base and flexible base is seen in top column bending moment for soft, medium and hard soil respectively for seismic zone III, zone IV and zone V.

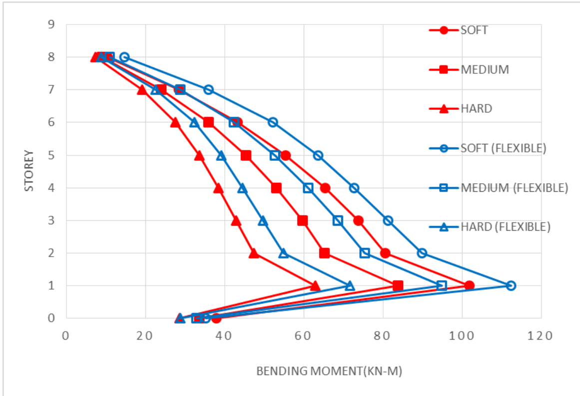

Chart -13: Variation of column bending moment with flexibility of soil for zone III

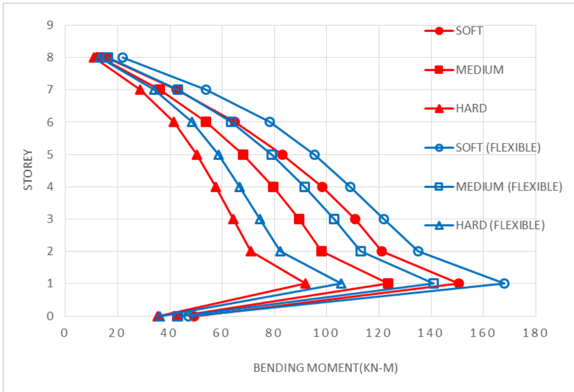

Chart -14: Variation of column bending moment with flexibility of soil for zone IV

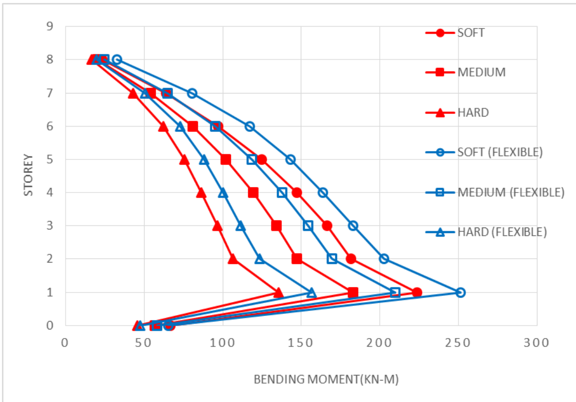

Chart -15: Variation of column bending moment with flexibility of soil for zone V

5.7 Variation in beam bending moment

It is observed that for top beam and middle beams there is no effect of seismic zone and flexibility of soil condition. For bottom beam as flexibility of soil increases bending moment in beam increased. A variation of 102.87% and 257.148% in comparison with seismic zone III is seen in bottom beam shear force for zone IV and zone V respectively for soft soil with fixed base condition. A variation of 72.60% and 181.65% in comparison with seismic zone III is seen in bottom beam shear force for zone IV and zone V respectively for soft soil with flexible base condition.

Table -5: Values of beam bending moment for seismic zone III

BM at		Bottom beam
Fixed base	Soft	22.657
	Medium	13.99
	Hard	3.921
Flexible base	Soft	37.255
	Medium	24.984
	Hard	11.026

Table -6: Values of beam bending moment for seismic zone IV

BM at		Bottom beam
Fixed base	Soft	45.965
	Medium	32.961
	Hard	17.857
Flexible base	Soft	64.302
	Medium	47.418
	Hard	27.525

Table -7: Values of beam bending moment for seismic zone V

BM at		Bottom beam
Fixed base	Soft	80.919
	Medium	61.418
	Hard	38.762
Flexible base	Soft	104.928
	Medium	81.068
	Hard	52.289

5.8 Shear stress in raft

Variation of shear stress in raft due to different earthquake zone for building frame with different soil conditions has been studied. The values of shear stress in raft are given in table 8. It is observed that as flexibility of soil increases shear stress in raft increases. As the seismic zone become severe value of shear stress in raft also increases. A variation of 26.77% is observed in seismic zone III soft soil compared to hard soil. A variation of 15.52% is observed in soft soil seismic zone V compared to zone III.

Table -8: Values of shear stress in raft (N/mm2)

ZONE	Soft soil	Medium soil	Hard soil
III	1.61	1.38	1.27
IV	1.64	1.5	1.35
V	1.86	1.69	1.48

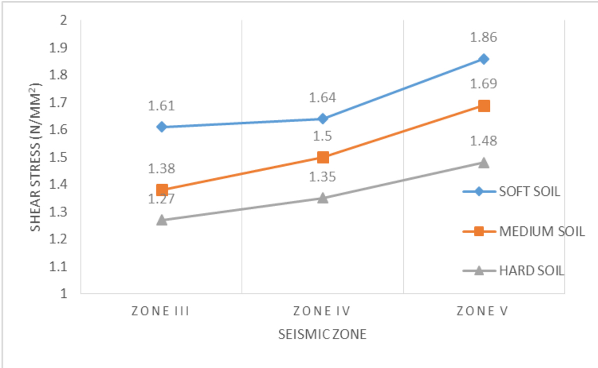

Chart -16: Variation of shear stress in raft with seismic zones

5.8 Bending moment in raft

Variation of bending moment in raft due to different earthquake zone for building frame with different soil conditions has been studied. The values of bending moment in raft are given in table 9. It is observed that as flexibility of soil increases bending moment in raft increases. As the seismic zone become severe value of bending moment in raft also increases. A variation of 21.5% is observed in seismic zone III soft soil compared to hard soil. A variation of 24.69% is observed in soft soil seismic zone V compared to zone III.

Table -9: Values of bending moment in raft (kN-m/m)

ZONE	Soft soil	Medium soil	Hard soil
III	243	232	200
IV	266	252	211
V	303	282	230

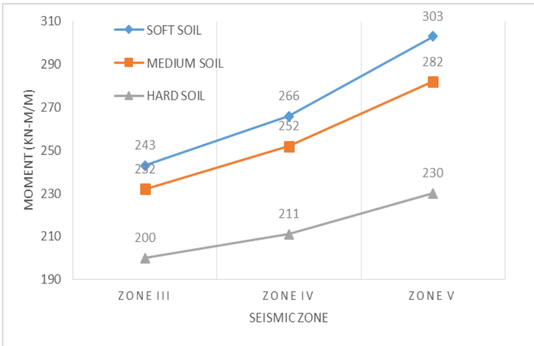

Chart -17: Variation of bending moment in raft with seismic zones

5.8 Settlement of raft

Variation in settlement of raft due to different earthquake zone for building frame with different soil conditions has been studied. The values of raft settlement are given in table 10. It is observed that as flexibility of soil increases settlement of raft increases. As the seismic zone become severe value of settlement also increases. A variation of 24.02% is observed in soft soil seismic zone V compared to zone III.

Table -10: Values of settlement of raft (mm)

ZONE	Soft soil	Medium soil	Hard soil
III	21.07	4.67	1.66
IV	23.05	5.04	1.75
V	26.13	5.60	1.90

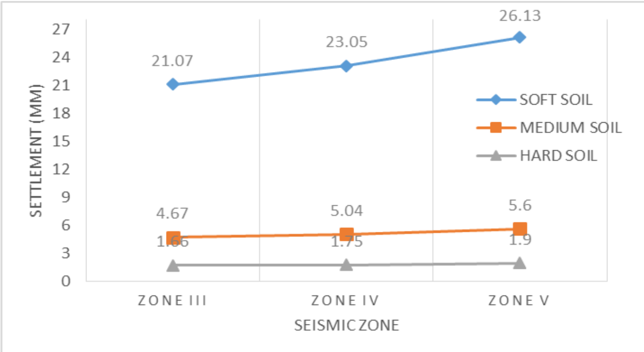

Chart -18: Variation in settlement of raft with seismic zones

6. CONCLUSIONS

The present work attempts to study the effect of soil structure interaction under seismic loading for eight storey R C building with raft foundation. Also an attempt is made to study effect of the soil structure interaction on building with different seismic zones. This study has been mainly carried out to determine the change in various seismic response quantities due to consideration of flexibility of soil and the effect of seismic zones. Following conclusions were drawn from the present study.

1) The study shows that natural period increase with soil flexibility. It is observed that an increase of 19.67% in natural period for soft soil condition.
2) Since natural period increases for flexible base condition, base shear has reduced for flexible base comparison with fixed base analysis. Thus, evaluation of these parameters without considering Soil Structure Interaction cause significant error in seismic design, as seismic response is found to be sensitive to SSI.
3) For seismic zone III, zone IV and zone V, the variation of 51.72%, 27.56% and 20.84% in comparison with fixed base and flexible base is seen for roof displacement in soft, 6medium and hard 6soil respectively.
4) The analysis of soil-foundation-structure system reports considerable increase in the column stress resultants and beam stress resultants with the fixed base assumption.
5) Response of structure increases with change in soil type from hard to soft and change in seismic zone III to zone V irrespective of height of structure.
6) A considerable variation is observed in raft shear stress and bending moment for soft and medium soil type compared to hard soil.
7) The study shows that there is considerable settlement of raft in soft soil, hence soil structure interaction is very much necessary in flexible soils.

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