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Effect of foundation conditions on the seismic response of a space frame

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ABSTRACT : Seismic analysis of a space frame has been carried out to find the influence of the foundation and soil conditions. Results have been presented for two different ground response spectra.

1. INTRODUCTION

The response of a structure during an earthquake depends on the characteristics of the ground motion, surrounding soil and the structure itself. The soil-structure interaction results from the scattering of waves from the foundation and the radiation of energy from the structure due to structural vibrations. In turn, the dynamic response of the structure may vary with the underlying soil conditions.

The effect of soil-structure interaction is analysed by introducing spring and dashpot or impedance function to represent the soil behaviour. Some authors (ASCE, 1986) have suggested that soil-structure interaction may not be considered in the seismic analysis for the structures supported on rock or rock like materials which are defined by shear wave velocity of 1100 m/sec or greater at a shear strain of 0.001 percent or smaller when considering preloaded soil conditions due to the structures. A comparison of fundamental frequencies of the fixed-base and interacting structures can be used to justify the fixed-base assumption (USNRC, 1982).

This paper attempts to examine the effects of the following on the distribution of natural frequencies of the structure and seismic structural response : Soil conditions, input response spectrum and foundation of the super-structure (i.e. raft, isolated footings or fixed-base). The case study has been carried out for a space frame.

2. THEORY

The governing differential equation for the dynamic response of the structure together with soil springs modelled by using a finite element formulation can be written as

$$[M]\ \{\ddot{x}\} + [C]\ \{x\} + [K]\ \{x\} = -\ [M]\ \{1\}\ \ddot{U}g \qquad \text{-----(1)}$$

Where the symbols have their usual meanings.

The shear wave velocity 'Vs'of the soil medium is given by : $Vs = \sqrt{Gs/\rho_s}$ Where Gs = Shear modulus of the soil and ρ_s= Mass density of the soil.

The soil spring stiffnesses for translation and rotation for rectangular foundation are calculated as per reference (Arya et al, 1979).

3 NUMERICAL ANALYSIS

A finite element analysis has been carried out for the space frame structure as shown in Figure 1. The structural and material properties for the structure are defined in Table-1. The columns and floor beams are modelled as 3-D beam elements. Floor slabs are modelled as quadrilateral plane stress elements. The raft is modelled as a thin plate and shell element incorporating membrane and bending effects.

The analysis has been done for a wide range of soil conditions from a very loose soil to very stiff soil. Here, the variable parameter involved is the shear wave velocity (Vs) of the soil medium. In the present study, a wide range of Vs, covering the values commonly encountered, from 50 m/sec to 5000 m/sec has been considered.

The analysis has been done for three different cases as described below :

1. Case 'A': The super-structure rests over a raft foundation overlying a homogeneous half space representing the soil medium.
2. Case 'B': The super-structure columns rest on rigid isolated footings over the surface of the homogeneous half space representing the soil medium.
3. Case 'C': The super-structure has a fixed-base.

Table-2 and Figure 2 present eigenvalues (natural frequencies of vibration) for cases A, B and C for the first few modes.

The analysis has been done for two different ground response spectra RS-1 (Sharma et al, 1990) and RS-2 (USNRC, 1982) as shown in Figure 3. The material and soil damping of 5% has been considered.

The analysis is based on the response spectrum method. The seismic input includes two horizontal and the vertical components of the ground motion in combination. The spectral values for the two horizontal ground motions are same and that for the vertical ground motion is 0.67 times the value for horizontal ground motion. The structural responses due to individual modes are combined according to the CQC rule.

Some typical results are presented in the paper. Figures 4 and 5 present column moment against Vs at the bottom of element 29 (see Figure 1) for the two response spectra. Response at the top of element 38 is given in Figures 6 and 7. Figures 8 and 9 present axial force in column against Vs (element 29). Figures 10 and 11 present beam bending moment against Vs (element 15). Figure 12 presents the raft moment against Vs for the case A.

Drawing an analogy with a single degree of freedom structure the effective stiffness (Ke) in case A can be approximated as

$$(1/Ke) = (1/Kss) + (1/Kr) + (1/Ks) \qquad \text{-----(2)}$$

Where Kss, Kr and Ks are the stiffness of the super-structure, raft and soil respectively. One needs to consider only Kss and Ks for case B and Kss for case C. With increasing Vs (hence, increasing Ks) the effect of soil stiffness diminishes. Thus for realistic structures (where Kr>>Ks), the effective stiffness in the three cases A,B and C approach an asymptotic value with increasing Vs. Hence, the seismic response (i.e. displacement, force and moment) in the three cases can also be expected to asymptotically reach the same limit as the Vs of soil increases.

From the response shown in Figures 4,5,6 and 7, it is seen that the column moment could be underestimated if the analysis assumes a fixed-base condition. The underestimation is more pronounced in case A and at relatively lower values of Vs. The same is true for axial force in column and moment in beams as seen in Figures 8-11. The increasing stiffness with Vs causes the raft displacements to be reduced, hence the raft moment reduces with increasing Vs (see Figure 12). The variation of the results between the cases A and B (i.e. raft foundation and isolated footings) arises mainly due to the differences in the natural frequencies of the two systems.

4. CONCLUSIONS

1. The first few natural frequencies of vibration for the structure are found to approach an asymptotic value with the increase in Vs of soil medium. The variation in the frequencies of vibration is seen to be significant for higher modes.
2. Neglecting the structure-foundation-soil interaction for a structure could result in significant underestimation of structural displacements and forces. In the present case study, larger difference in the responses have been observed for the same structure having raft foundation and having isolated footings for lower Vs of soil medium. These differences are more pronounced for structural members closer to the foundation.
3. In the present study it is observed that, as Vs increases little beyond 1100 m/sec, the response of the structure approaches fixed-base condition for isolated footings. However, for raft foundation this limit is reached at a much higher Vs of the soil medium.

REFERENCES

Arya, S.C., M.W. O'Neill and G. Pincus, 1979. "Design of Structures and Foundations for Vibrating Machines", Gulf Publishing Co., Houston.

ASCE-ASCE Standard 4-86, 1986. "Seismic Analysis of Safety-Related Nuclear Structure and Commentary on Standards for Seismic Analysis of Safety- Related Nuclear Structures", American Society of Civil Engineers, New York, USA.

Sharma, R.D., A.K. Ghosh, D.C. Banerjee and U.S.P. Verma, 1990. Final Report on Seismotectonics and Earthquake Design Basis for Kaiga-1 & 2, NPCIL, Department of Atomic Energy, Bombay.

USNRC, 1982. Standard Review Plan 3.7.2, NUREG 800, US Nuclear Regulatory Commision.

Table-1
Description of Structural and Material Properties for the Structure

(Unit : KN-M)

Structure
1. Raft foundation : 6.0 x 6.0 x 0.3
2. Isolated footings : 1.0 x 1.0 (plan area)
3. Columns : 0.5 x 0.5
4. Floor beams : 0.23 x 0.4
5. Floor slab thk. : 0.15
Concrete
1. Grade : M 20
2. Modulus of elasticity : 0.255E08
3. Poission's ratio : 0.15
4. Weight density : 25.0

Table-2
Comparison of Natural Frequencies of Vibration

Frequency value in 'Hz'

Mode No	Shear Wave Velocity (m/sec.)						C
	50.00		1100.00		5000.00		
	A	B	A	B	A	B	
1	2.35	3.31	4.35	4.40	4.40	4.41	4.41
2	2.35	3.31	4.35	4.40	4.40	4.41	4.41
3	3.50	4.23	5.25	5.27	5.29	5.29	5.29
4	4.76	9.59	14.80	14.92	14.91	14.93	14.93
5	4.76	9.59	14.80	14.92	14.91	14.93	14.93
6	7.76	10.94	16.20	16.34	16.34	16.35	16.35
7	9.06	14.42	43.39	48.98	49.15	50.40	50.48
8	12.53	14.53	44.66	58.69	57.34	60.47	60.56

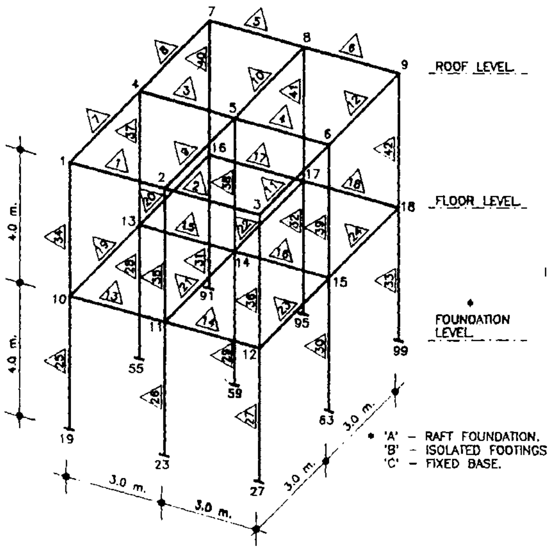

FIG-1 - SPACE FRAME STRUCTURE.

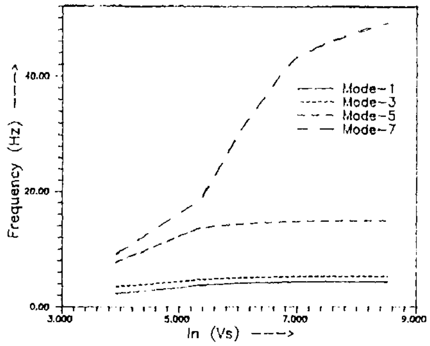

Fig. 2 : Natural Frequencies of Vibration for case 'A'

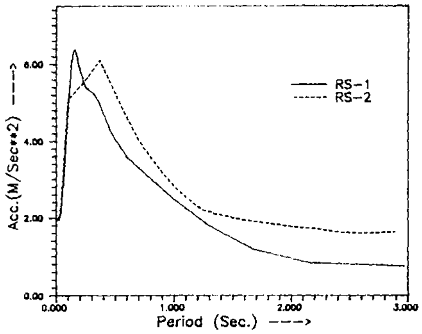

Fig. 3 : Response Spectra

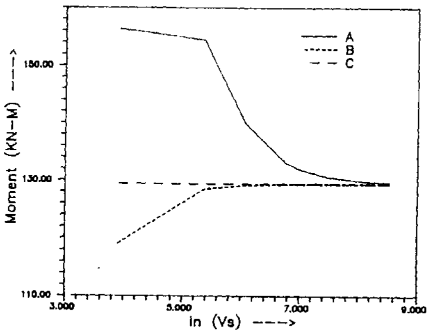

Fig. 4 : Column Moment at the Bottom for Element '29' (RS-1)

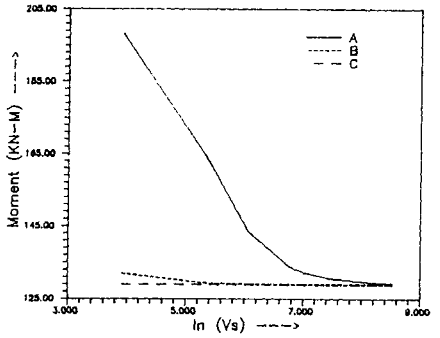

Fig. 5 : Column Moment at the Bottom for Element '29'(RS-2)

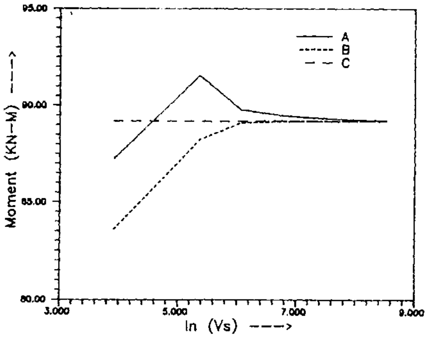

Fig. 6 : Column Moment at the Top for Element '38'(RS-1)

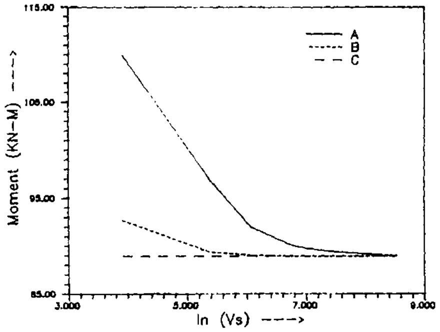

Fig. 7 : Column Moment at the Top for Element '38'(RS-2)

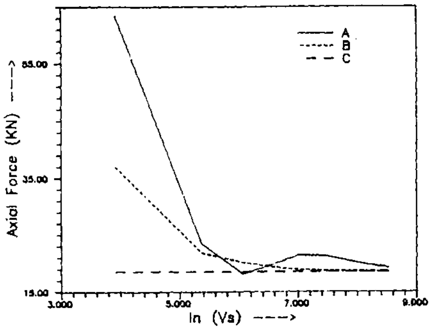

Fig. 8 : Column Axial Force for Element '29' (RS-1)

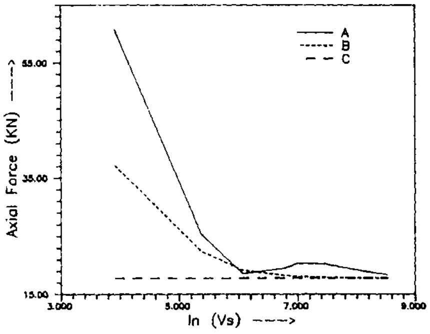

Fig. 9 : Column Axial Force for Element '29' (RS-2)

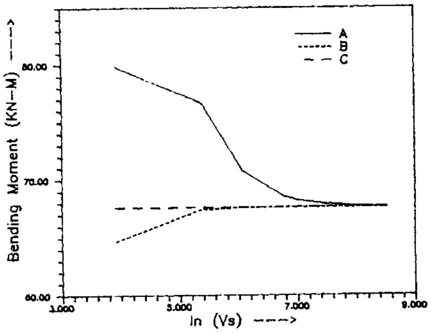

Fig. 10 : Beam Bending Moment for Element '15' (RS-1)

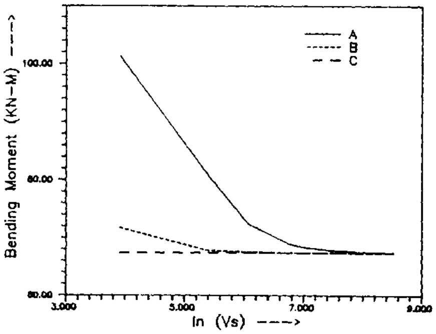

Fig. 11 : Beam Bending Moment for Element '15' (RS-2)

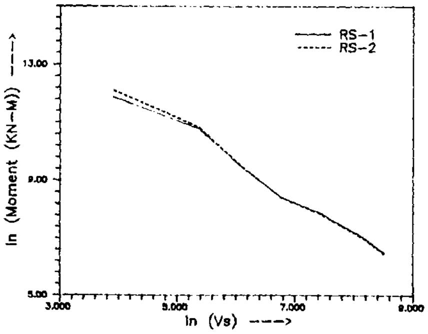

Fig. 12 : Raft Moments at Node no '59'