Experimental Investigation of Building Frame Considering Soil Structure Interaction

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Abstract— Seismic response of structures is extremely complex because of the unpredicted behavior of soils during earthquakes. Structures founded on rock are considered to be fixed-base structures. On the other hand, the same structure will respond differently if supported on a soft soil deposit. The response of the soil influences the motion of the structure and response of the structure influences the motion of the soil. This is referred to as Soil-Structure Interaction (SSI). SSI effects account for the flexibility of the foundation support beneath the structure and potential variations between foundation and free-field motions. Earlier studies have indicated that, interaction effect is quite significant, particularly for the structure resting on compressible soil.

Keywords: Soil, Structure, Interaction, Soil-Foundation, Earthquake

I. Introduction

Soil-structure interaction is inter-disciplinary field which involves structural and geotechnical engineering. In the conventional analysis of building frame structural designer assumed that columns are resting on unyielding support. Similarly, in foundation design, foundation settlements are calculated without considering the influence of the structural stiffness. Although, interaction effect is ignored to simplify the mathematical model but neglecting the interaction between soils and structures may result in a design that is either unnecessarily costly or unsafe. A more rational solution of soil-structure interaction problem can be achieved with computational validity and accuracy by appropriate analysis.

The search for a physically close and mathematically simple model to represent the soil-media in the soil–structure interaction problem shows two basic classical approaches, viz., Winklerian approach and Continuum approach. At the foundation-supporting soil interface, contact pressure distribution is the important parameter. The variation of pressure distribution depends on the foundation behavior (viz., rigid or flexible: two extreme situations) and nature of soil deposit (clay or sand etc.).

Since the philosophy of foundation design is to spread the load of the structure on to the soil, ideal foundation modeling is that wherein the distribution of contact pressure is simulated in a more realistic manner. From this viewpoint, both the fundamental approaches have some characteristic limitations. However, the mechanical behavior of subsoil appears to be utterly erratic and complex and it seems to be impossible to establish any mathematical law that would confirm to actual observation. In this context, simplicity of models, many a time, becomes a prime consideration and they often yield reasonable results.

Fig 1.1: 1985 Mexico City earthquake & 1995 Kobe earthquake

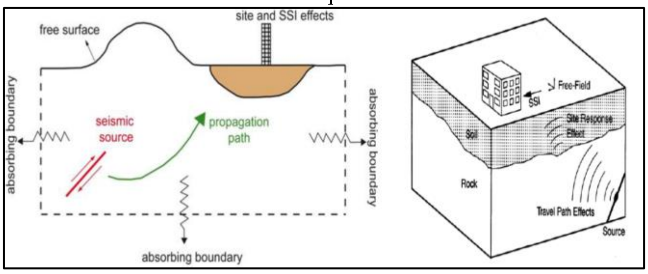

Fig 1.2: Soil Structure Interaction Phenomenon

a) Tall buildings b) Chimney

c) Nuclear power plants d) Elevated service reservoir

Fig 1.3: Different SSI Significant Structures

II. Literature Review

The SSI concept is being used in research field since last 70 years. Basic superposition of wave fields is discussed as a common basis for different approaches – direct and impedance ones. Many of the researchers have performed study work in the same field and study work of some of the recent researchers working the field of SSI is as mentioned below.

George Gazetas (1991) derived and presented the formulae and charts for impedances of surface and embedded foundations. A complete set of algebraic formulas and dimensionless charts is presented for readily computing the dynamic stiffness (K) and damping coefficients (C) of foundations harmonically oscillating on/in a homogeneous half-space. All possible modes of vibration, a realistic range of Poisson's ratios, and a practically sufficient range of oscillation frequencies are considered. The foundations have a rigid basement of any realistic solid geometric shape.

Sekhar Chandra Dutta et al. (2004) studied SSI of low-rise building frames resting on shallow foundations, viz. isolated and grid foundation. Influence of soil–structure interaction on elastic and inelastic range responses of such building frames due to seismic excitations has been examined in details. Representative acceleration–time histories such as artificially generated earthquake history compatible with design spectrum, ground motion recorded during real earthquake and idealized near-fault ground motion, have been used to analyze the response. Variation in response due to different influential parameters regulating the effect of soil-flexibility is presented and interpreted physically.

Nam-Sikkimet al. (2004) has conclude that although there are several experimental techniques to evaluate the seismic behavior and performance of civil structures, small-scale models in most of physical tests, instead of prototypes or large-scale models, would be used due to a limitation on capacities of testing equipments. However, the inelastic seismic response prediction of small-scale models has some discrepancies inherently because the similitude law is generally derived in the elastic range. Thus, a special attention is required to regard the seismic behavior of small-scale models as one of prototypes. In this paper, differences between prototypes and small-scale models pseudo-dynamically tested on steel column specimens are investigated and an alternative to minimize them is suggested. In general, small-scale models could have the distorted stiffness induced from some experimental errors on test setup, steel fabrication and so on. Therefore, a modified similitude law considering both a scale factor for length and a stiffness ratio of small-scale model to prototype is proposed.

B. R. Jayalekshmi et al. (2008) has evaluated the Soil-Structure-Interaction (SSI) effects on the seismic response of structures founded on Shedi soil of Dakshina Kannada. Shedi soil, which is a dispersive type of soil is highly vulnerable to dynamic loading in the saturated condition. Experimental investigations have been carried out on 1:10 scaled single bay three dimensional multi storey building models made of aluminum with its foundation resting on locally available Shedi soil (classifying as sandy silt) and sand in the saturated and dry conditions. The combined system of Soil-Foundation-Structure models is subjected to dynamic loading. The response of the model is measured at each floor level. This structural response is compared with that of a fixed base model to isolate the effect of soil structure interaction. The variations in natural frequency with various parameters such as different types of soil, degree of saturation of soil, number of storeys and the stiffening effect of walls are evaluated. The experimental results are presented and the modifications in dynamic characteristics due to the incorporation of soil flexibility are studied.

Quintana-Gallo P. et al (2010) have conducted quasi-static test of 2/3 scale beam column joint subassemblies representative of pre-70s reinforced concrete (RC) frame buildings, referred as under-designed structures (non-ductile detailing, no capacity design principles), before and after retrofit. As a dynamic validation of the seismic vulnerability of such structures and the feasibility of the developed and improved retrofit solutions, a series of 4 1/2.5 scale experimental models (two 3 storey - 2 bay frames jointed together by transverse beams and floor slabs) were tested on the Shake Table, without and with a seismic retrofit intervention and without and with infill panels.

Akanshu Sharma et al. (2012) tested a reinforced concrete (RC) framed structure detailed according to non-seismic detailing provisions as per Indian Standard on shake table under dynamic loads. In order to optimize the information obtained from the tests, tests were planned in three different stages. In the first stage, tests were done with masonry infill panels in one direction to obtain information on the stiffness increase due to addition of infill panels. In second stage, the infill were removed and tests were conducted on the structure without and with tuned liquid dampers (TLD) on the roof of the structure to investigate the effect of TLD on seismic response of the structure. In the third stage, tests were conducted on bare frame structure under biaxial time histories with gradually increasing peak ground acceleration (PGA) till failure.

Dr. S.A Halkude, M.G Kalyanshetti, S.H Kalyani, (2013) studied soil structure interaction effect on seismic response of R.C. frames with isolated footing and concluded that Natural period, Roof displacement, Base shear, Beam moment and Column moment are observed to be increasing with increase in soil flexibility. FEM models are Much Idealized Realistic model than spring model. Finite Element Method has proved to be a very useful method for studying the effect of SSI.

Dhiraj Raj and Bharathi M (2013) has been analyzed a four storied reinforced concrete (RC) building (without bracing and with bracing of different types at different locations), located in seismic zones IV and V, founded on three different types of soils as per IS 1893(Part I):2002 with the fixed and flexible foundation. The building with the flexible foundation has been analyzed incorporating soil-structure interaction (SSI) effects as per FEMA 356 and FEMA 440. Fifty different combinations of the same RC building without bracings, with bracings, seismic zones and types of soils have been analyzed as per various codes. The results in terms of the responses of all the building are presented in the form of tables and chart.

III. METHODOLOGY

Two different approaches have been adopted in the past to investigate the problem of soil structure interaction and incorporate the effect of soil compliance in the dynamic analysis. a) The direct approach b) The sub-structure approach.

A. Direct Approach

In the direct method, the structure and a finite bounded soil zone adjacent to the structure (near field) are modeled by the standard finite-element method and the effect of the surrounding unbounded soil (far field) is analyzed approximately by imposing transmitting boundaries along the near-field/far-field interface. The soil is often discretized with solid finite elements and the structure with finite beam elements. Since assumptions of superposition are not required, true nonlinear analyses are possible. Many kinds of transmitting boundaries have been developed over the past two decades to satisfy the radiation condition, such as a viscous boundary, a superposition boundary, and several others. However, results from nonlinear analyses can be quite sensitive to poorly-defined parameters in the soil constitutive model, and the analyses remain quite expensive from a computational standpoint.

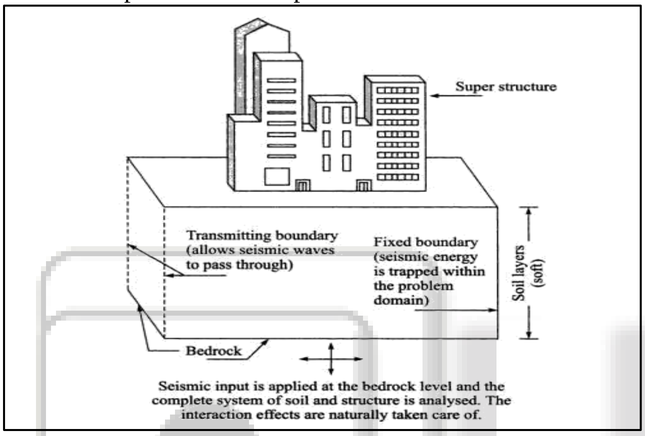

Fig. 3.1: Modeling for Analysis of Soil Structure Interaction Effect by Direct Method

B. Substructure Approach

The substructure method is more complex than the direct method in modeling the SSI system. In the substructure method, the soil–structure system is divided into two substructures: a structure, which may include a portion of non-linear soil or soil with an irregular boundary, and the unbounded soil. These substructures are connected by the general soil–structure interface, as shown in Figure 3.2.

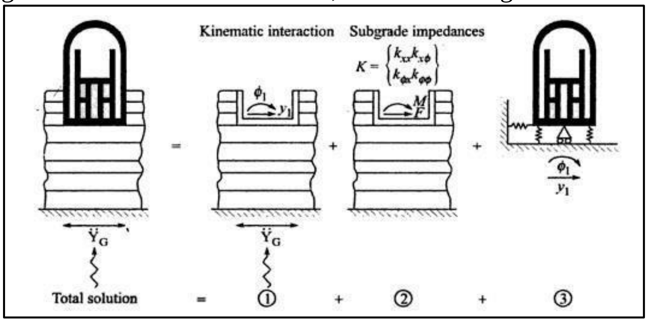

Fig. 3.2: Soil Structure Interaction Analysis by Substructure Method

It should be noted that, if the structural foundations were perfectly rigid, the solution by substructure approach would be identical to the solution by the direct method. Generally, foundation input motion is assumed to be the same as free-field motion, i.e. the effects of kinematic interaction are neglected in SSI analysis for most of the common constructions Kinematic interaction should invariably be considered if the structure and foundations to be constructed are very massive, rigid and very large.

IV. EXPERIMENTAL STUDY

The present study aims to evaluate the experimental performance of three RC building frames considering SSI. The prototype structure cannot be tested in laboratory directly due to limitations of size and payload capacity of Shake Table. Therefore, it is essential to carry out the study on a scaled-down model which can be conveniently tested on Shake Table and thereafter the results obtained are extrapolated back to prototype structure using similitude laws. Therefore, scaled-down model is required to be designed and prepared judiciously as the performance of the prototype structure is evaluated based on the performance of the scaled down model in the laboratory.

Prototype RC Building Frame Considered for the Analysis

Sr. No	Contents	Description		
1	Structure	OMRF	OMRF	OMRF
2	No. of stories	G+3	G+5	G+7
3	Storey Height	3.5 m	3.5 m	3.5 m
4	Grade of Concrete	M 25	M 25	M 25
5	Grade of Steel	Fe415	Fe415	Fe415
6	Bay width	4 m.	4 m.	4 m.
7	Slab thickness	0.15 m	0.15 m	0.15 m
8	Size of Column	0.45m x 0.3m	0.40m x 0.25m	0.45m x 0.3m
			0.45m x 0.45m	0.55m x 0.50m
9	Size of Beam	0.4m x 0.23m	0.4m x 0.23m	0.4m x 0.23m
10	Floor finish	0.6 kN/m²	0.6 kN/m²	0.6 kN/m²
11	Live load	4 kN/m²	4 kN/m²	4 kN/m²
12	Seismic Zone	III	III	III

Table 4.1: Geometric and material properties of building frame

In the present work, three prototype RC building frames G+3, G+5 and G+7 is considered. The building frames considered are square in plan with single bay in both directions. The geometry of building frames are decided based on the feasibility of experimental study on scale down steel model. The details of dimensional characteristics are illustrated in Table 4.1. above.

1) Scale Factor:-

Adopting appropriate geometric scale factor is one of the important steps in scale modeling on shaking table.

Due to size limitation of shake table, the plan dimension of model is set as 0.32m.

Thus, the C/C distance between two columns is set as

0.32 m leading to a linear scale factor, of 4.0/0.32 = 12
Therefore, Scale Factor (SL)=12.5

Employing geometric scaling factor of 1:12.5 as explained above height, length, and width of the structural model are determined to be, 1.120 m, 0.32 m and 0.32 m, respectively.

The scaling relationship between natural frequency of the model (*fm)* and natural frequency of the prototype (*fp)* is

$fm/ fp = S_L^{1/2} = 3.54$

frequency of the prototype structure is

fp = 1.4792 Hz

= 1.4792 × 3.54 = 5.24 Hz

The density of the model (ρm) should be equal to the density of the prototype (ρp).

Density of the prototype structure (ρp) is determined as follows:

ρp = mass of prototype / volume of prototype

= 59140 / (14×4×4)

= 264.01 Kg/m³

Therefore, the mass of the structural model (Mm) is estimated as:

Mm = ρm × Vm = 264.01 × (1.12×0.32×0.32)

= 30.27 Kg

Parameters	Scale Factor
	1
Stiffness	S2
Force	S3
Modulus	S
Acceleration	1
Frequency	S-1/2
Time	S1/2
Shear Wave Velocity	S1/2
Length	S
Stress	S
Strain	1
EI	S5

Table 4.2: Scaling Relations in Terms of Geometric Scaling Factor (S)

The dimensions of column and slab of scale down steel model is derived in such a way that the weight of model nearly equals to 30.27 Kg as required by simulated laws. Considering all above the details of G+ 3 scale down steel model is worked out. Similar calculations were done for G+5 and G+ 7 steel models and the details of all scale down models are presented in Table 4.3.

Sr. No	Contents		Description	
1	No. of stories	G+3	G+5	G+7
2	Storey Height	280mm	280mm	280mm
3	Grade of Steel	Fe250	Fe250	Fe250
4	Bay width	320mm	320mm.	320mm
5	Slab thickness	4mm	3mm	3mm
6	Size of Column	10mm X 10mm	12mm X 12mm	12mm X 12mm
7	Size of Plinth Beam	10mm X 10mm	12mm X 12mm	12mm X 12mm

Table 4.3: Geometric and material properties of scale down steel mode

A typical G+3 scale down steel model details are given in Figure 4.1

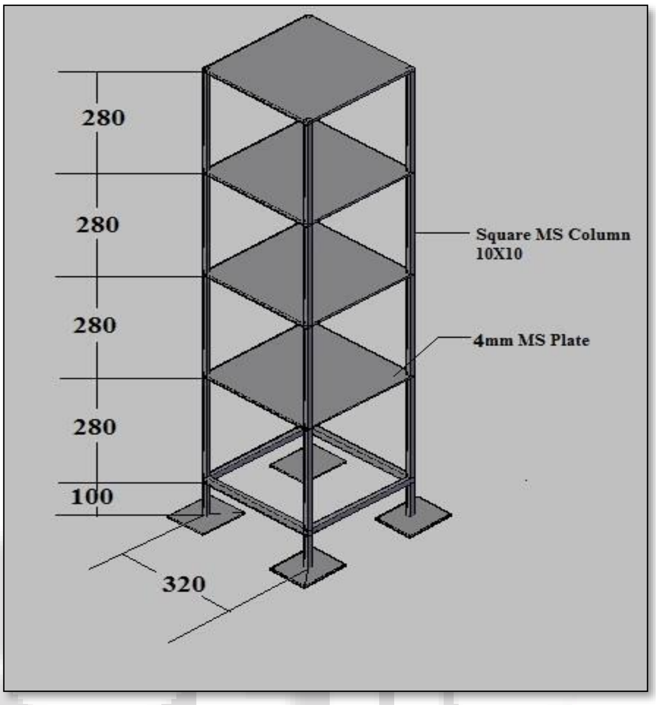

Fig 4.1: Typical View of G+3 Scale Down Steel Mode

2) Shake Table: -

Shake Table is a most appropriate experimental set up for the prediction of seismic behavior of various civil engineering structures. Structural models are directly subjected to dynamic excitations resembling those expected to be encountered in a real time earthquake event. It is possible to realistically simulate the effect of seismic forces on the test structures on Shake Table. The full dynamic loading property makes Shake Table testing an effective tool in the research field. There are two significant challenges for adopting the Shake Table technique, firstly, dynamic similitude scaling requirements, and secondly, the control of table motions to ensure the reproduction of target accelerations. Dynamic hydraulic equipment generally has a lower force capacity than static apparatus of similar cost, so Shake Table systems have traditionally been assembled with capacity, too low to test full scale civil engineering structures.

Fig. 4.2: - Shake Table

The table is designed with a natural frequency of 50 Hz and the design also ensures that the center of gravity of the test object can lie anywhere within the table and elevated up to 1000 mm above the table. The precision machined table engages with the linear bearings and provide the linear horizontal movement. The specifications of this shake table are given in Table 4.4.

Sr.	Particulars	
1	Table size in mm	2000 X 2000
2	Capacity	30 kN
3	Servo hydraulic actuator	100 kN capacity
4	Maximum acceleration	2g
5	Accelerometers	Dual axis 2 g, 100 Hz-4nos
6	Frequency range	0.01 Hz – 50 Hz
7	Servo hydraulic power	65 LPM, pressure 0-210 bar
8	Hydraulic UPS	10 L capacity accumulator charged with Nitrogen gas at 100
9	AC- 04-03 UACE 20-20 Digital servo controller	
10	AC- 08- 0101 Single axis seismic shake table application software	

Table 4.4: Specifications of Shake Table

3) *Experimental Setup on Shake Table: -*

An experimental study is carried out in order to validate the theoretical soil-structure interaction response. The scaled down steel model explained in section 4.3 is used for the study. Two base conditions i.e. “Fixed-base” and “Flexible-base” are taken into account for the SSI evaluation process. The former refers to the building founded on infinitely rigid base and the latter refers to the building founded on a soil deposit producing flexibility at base.

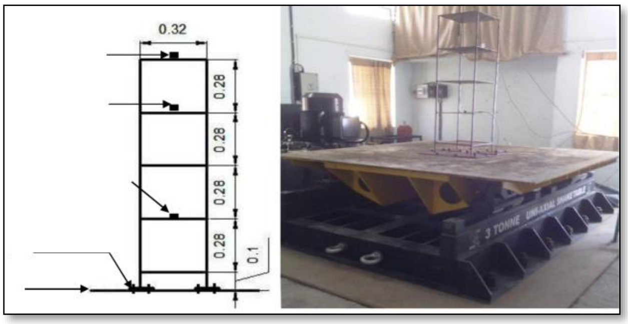

Fig. 4.3: Experimental Set Up for Fixed Base Condition

4) *Flexible Base Condition:-*

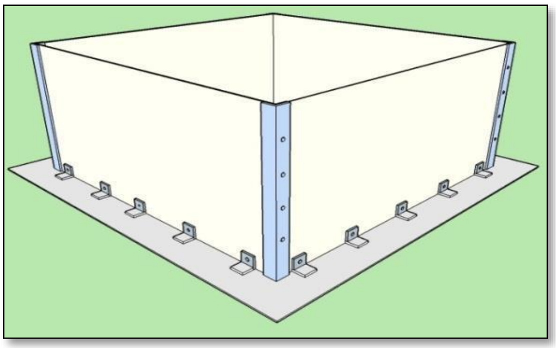

Fig. 4.4: Isometric View of Steel Tank

To simulate soil structure interaction condition in the laboratory a container made of steel plates is used as shown in Figure 4.4. This container is used to hold the soil mass beneath the foundation. The container is mounted on shake table.

The finite soil mass is considered based on convergence study, with boundary far beyond a region where structural loading has no effect. This is assumed to be at a lateral offset of two times width of the building on all four sides and depth equal to 3 times the width of building. As per this guideline soil block of 1.6x1.6 m in plan is required. However, considering limitation of Shake Table, container of size 1.5x1.5x0.7 m is used.

V. RESULTS AND DISCUSSION

The acceleration v/s. time plots obtained for all the accelerometers. In these figures, red line indicates the response of acceleration, green line of velocity and blue line of displacement. These values are obtained for all the three accelerometers placed at different predefined locations. The results are obtained for all the model i.e. G+1, G+2, G+3 and G+4 with fixed base condition and discussed below. The maximum acceleration, velocity and displacement is considered and variation of maximum acceleration, maximum velocity and maximum displacement is plotted.

Storey No.	Maximum Acceleration(m/s^2)	Maximum Velocity(m/s)	Maximum Displacement (mm)
1	0.9065	0.167	3.33
2	1.56815	0.30535	6.08
3	1.66599	0.3397	6.74
4	2.5235	0.4951	9.9

Table 4.6: Maximum acceleration velocity & Displacement

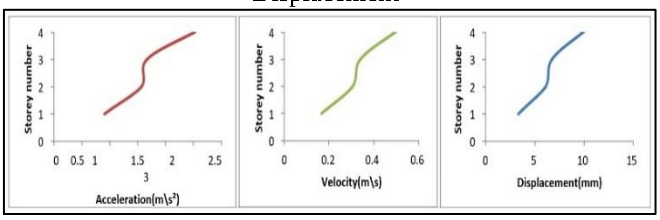

Fig. 4.5: Variation of Maximum Acceleration, Velocity and Displacement

The response of structure such as acceleration, velocity and displacement at all floor level of all building frame is determined for fixed and flexible base condition.

VI. CONCLUSION

The results obtained are presented in chapter based on these observations following conclusions are drawn: -

1) For all building frames it is observed that acceleration, velocity and displacement goes on increasing from ground level to roof level.
2) The rate of increase is observed relatively mild up to 3rd storey (in case of G+5 building), there onwards rate increases up to roof level.
3) Study reveals that SSI effect is structure specific and input motion specific.
4) Therefore, during Earthquake depending upon frequency content of motion certain class of building are subjected to damage. The SSI effect plays important role in the performance of building frames.
5) The present study advocates that all the structures shall be analyzed considering SSI effect for specific site response spectra.
6) The SSI study is carried out on a GW type of soil. The results presented are for this soil only. In case of change in soil separate study shall be carried out.

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