DESIGN COMPARISON OF INTEGRATED AND DISCRETE SUPER AND SUBSTRUCTURE BUILDING SYSTEMS UNDER SEISMIC LOADING

A.U. Qazi, M. S. Hanif*, N. M. Khan, M. B. Sharif, and A. Hameed

Department of Civil Engineering, University of Engineering and Technology, Lahore.
*Structural Division Nespak House, Lahore
Author burhansharif@uet.edu.pk

ABSTRACT: With the availability of digital computers and Finite Element Analysis (FEA) programs, super and substructure modeling as a combined entity is not a difficult task. Accurate judgment of available capacity of structure and foundation require the integrated modeling of structure-foundation system. To make the structure economical and safe, it is necessary that the interaction between super and substructure should be taken into consideration in the engineering design. However, structural engineers even to date model the structure with fixed base, and there is no representation of the foundation and soil strata underneath. This research compares the performance of integrated structure foundation models and discrete models by using general purpose FEA program. Analysis and design of reinforced concrete moment resistant multistory frame buildings have been carried out by integrated and discrete modeling approach. Linear static and linear dynamic analyses are performed on the hypothetical building models with integrated individual, strip and raft footings. Response is compared with the corresponding discrete building models. Effect of pad thickness and soil spring stiffness is also studied. In integrated modeling; it is observed that the stress in the superstructure is increased. However, buildings when modeled with fixed supports result in reduction of stresses in the superstructure because fixity in this case is not actual response by the foundation. Result of integrated models show close similarity with discrete models when the pad thickness and the soil spring stiffness are increased.

Keywords: Discrete model; integrated model; Building Systems; Stiffness; Response; spring stiffness.

INTRODUCTION

Integrated modeling of both the soil foundation and superstructure is a sophisticated and realistic approach. However, to model soil foundation and superstructure as a combined entity is very time consuming and computationally expensive. Hence, simplifications to both systems are required to analyze the integrated structure and foundation behavior. Three common methods to model shallow foundation in the previous research (Winkler (1867); Hetenyi (1946); Mindlin (1936); Lysmer and Kuhlemeyer (1969)) are Bed of Winkler springs, elastic continuum and finite element. Experimental and analytical studies have been undertaken by many researchers to understand the behavior of shallow foundations (Georgiadis and Butterfield 1988; Martin and Lam 2000; Pecker and Pender 2000). Winkler based Spring Model greatly reduces the computational effort of integrated modeling and reduces time with satisfactory level of accuracy (Liam M. W. 2009). Winkler (1867) and (Joseph E. B. 1996) represented the soil medium as a bed of closely spaced linear elastic springs. Displacement of each spring is independent of the other due to the discrete nature of the springs, and is related only to the contact pressure at that point. A relationship between deflection and soil pressure known as modulus of subgrade reaction is extensively used in the structural analysis of foundation. The basic equation when using plate-load test data is

$$k_s = \frac{q}{\delta} \quad \text{(I)}$$

Where q is the contact pressure, K_s is the coefficient of subgrade reaction and δ is the displacement. Due to simplicity and ease at which nonlinearity of soil can be modeled it can be used for all type of footings (Joseph E. B. 1996). Many researchers (Mehrotra, B. L. and Gupta Y.P. 1980; Karamaneas H. E. 2002) have done work on discrete and integrated raft models. It has been shown (Mehrotra, B. L. and Gupta Y.P. 1980) that with the raft-structure interaction the intensity of the maximum bending moment in the raft reduced up to about 25% of that given by the more conventional fixed supports. While, when considering the interaction between superstructure and raft foundation, superstructure will bear some load of the raft foundation as a result of release of moment and reduces the stress and strain in the raft and results in the increase of forces in the superstructure (Jian S. et al 2006). Martin and Lam (2000) also discussed the increased importance of an integrated modeling approach, particularly in the move towards the displacement based design approach.

A more realistic moment, shear and axial force distributions in the superstructure due to deformation of the raft will result in realistic use of concrete and steel. Currently FEA method is used for analysis of raft foundation design in high-rise buildings. Compared with other conventional methods, this is more adapted to the practical condition since both superstructure stiffness and soil conditions are considered in calculations. Accordingly, the raft foundation design is more economical without any loss of accuracy for the high-rise building. In the literature, there are two techniques available for raft foundation analysis and design. The first technique is "structural" that is the superstructure and raft integrated into one structural model. The second approach is "geotechnical" and that is to model the raft and subgrade "soil" in one analysis problem. The shortcoming of the structural alternative is that the subgrade reaction must be assumed and modeled mathematically beforehand. The shortcoming of geotechnical alternative is the lack of ability to model the superstructure interaction directly. This modern approach of integrating super and substructure offers the potential for modeling superstructure, foundation and geotechnical "subgrade - soil" component accurately. The study here includes the design comparison of integrated and discrete super and substructure raft models with equal and unequal adjacent spans. This study also includes the design of integrated strip and integrated isolated footings modeled with superstructure. These integrated super and substructure designs are then compared to that of corresponding discrete models. Effect of the thickness of the pad and soil spring stiffness is also studied.

Computer modeling: Linear static and linear dynamic analyses have been carried out on hypothetical building models 1 with the raft, strip and isolated footings. Buildings are modeled on SAP2000, ETAB-9 and SAFE commercial programs.

Building with Raft Foundation (Equal Spans): A six storey reinforced concrete building with 3.65m spans in each direction is studied. Six bays are selected in x and y-direction. The building has typical storey height of 3.65m. Primary grid on the plan for the discrete and integrated raft model is shown in Fig. 1.

Building with Strip Foundation: A five storey RC building is studied with 3.65m spans in x-direction and 10.67m span in y-direction. Five bays are in x-direction and one bay is in y-direction. The building has typical storey height of 3.65m. Primary grid on the plan for the discrete and integrated strip model is shown in Fig. 2.

Building with Isolated Foundation: A four storey RC building is selected for study with 4.57m spans in each direction. Three bays are in x-direction and y-direction. The building has no basement with typical storey height 3.65m. Primary grid on the plan for the discrete and integrated isolated footing model is shown in Fig. 3.

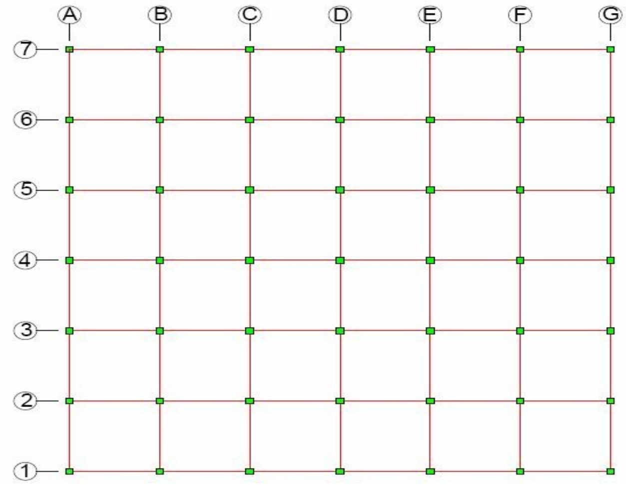


Figure 1: Plan for Discrete and Integrated Raft model

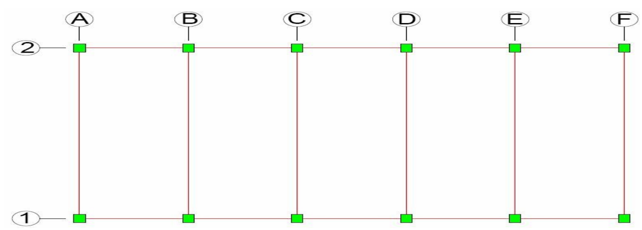


Figure 2: Plan for Discrete and Integrated Strip model

Design Basis and Strength of Materials: The strength of materials for discrete and integrated models is given in Table 1.

Table 1: Material Strength Properties

Properties	Raft/Strip/Isolated Footing
f'c	21MPa
fy	420MPa

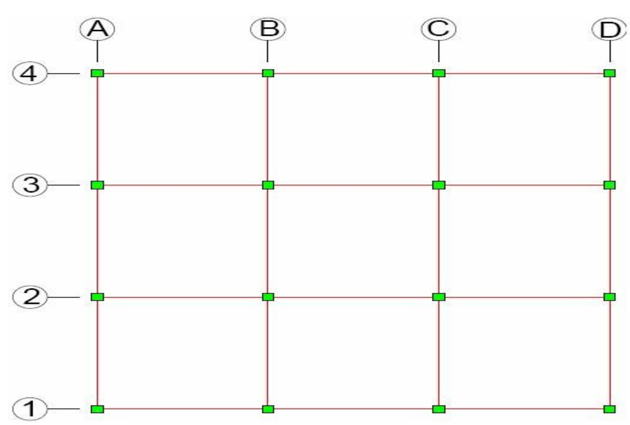


Figure 3: Plan for Discrete and Integrated Isolated Footing model

The seismic parameters used for discrete and integrated models are summarized in Table 2 are taken from PBC 2007.

Table 2: Seismic Analysis Parameters

Parameters	Raft/Strip/Isolated Footing
Zone	2A
Soil Type	SD
I	1.0
R	5.5

Table 3 describes various types of loads that are used to carry out the research work for discrete and integrated models.

Table 3: Design Load for Discrete and Integrated Models

Loads	Raft/Strip/Isolated Footings
Superimposed Load	$292 kg/m^2$
Live Load	$390 kg/m^2$

The raft and strip foundation thickness used in discrete and integrated models are 450mm and 525mm respectively. For discrete and integrated isolated footing model the foundation thickness under the corner, exterior and interior columns are 300mm, 375mm and 450mm respectively.

The soil springs in all the analysis models used are Winkler type springs and are calculated for the bearing capacity of 107kPa with allowable settlement of 25.4mm and is calculated as:

$$k_v = \frac{FOS \times BC}{\Delta} \quad \text{...II)}$$

$$k_v = \frac{3 \times 107 \times 1000}{25.4} = 12637.8 \text{ kN/m}^2\text{/m}$$

Where, FOS is factor of safety. BC stands for bearing capacity of the soil and Δ represents the foundation settlement. In ETABS-9 a commercial FEM program these springs are applied as area springs and equation II is basically derived from the basic plate load test as given in equation I which is the modulus of sub grade reaction.

DISCUSSION ON LINEAR STATIC ANALYSIS RESULTS

Discrete and Integrated Raft Model: With gravity loads combination,
$(1.2D_L+1.6L_L)$ ... (III)

the difference in the design is about 1% to 2% between discrete and integrated raft model both in the beams and columns,. While in case of gravity and lateral loads,
$(1.2D_L+1.0L_L+1.0EQ_X)$... (IV)
.

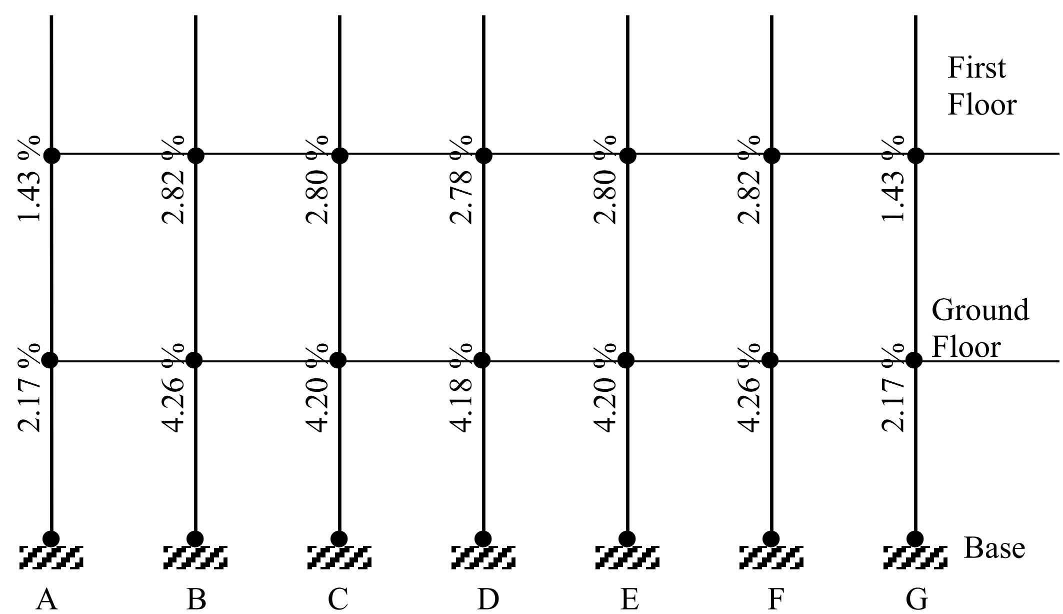


Figure 4 Discrete model (columns design) rebar ratio

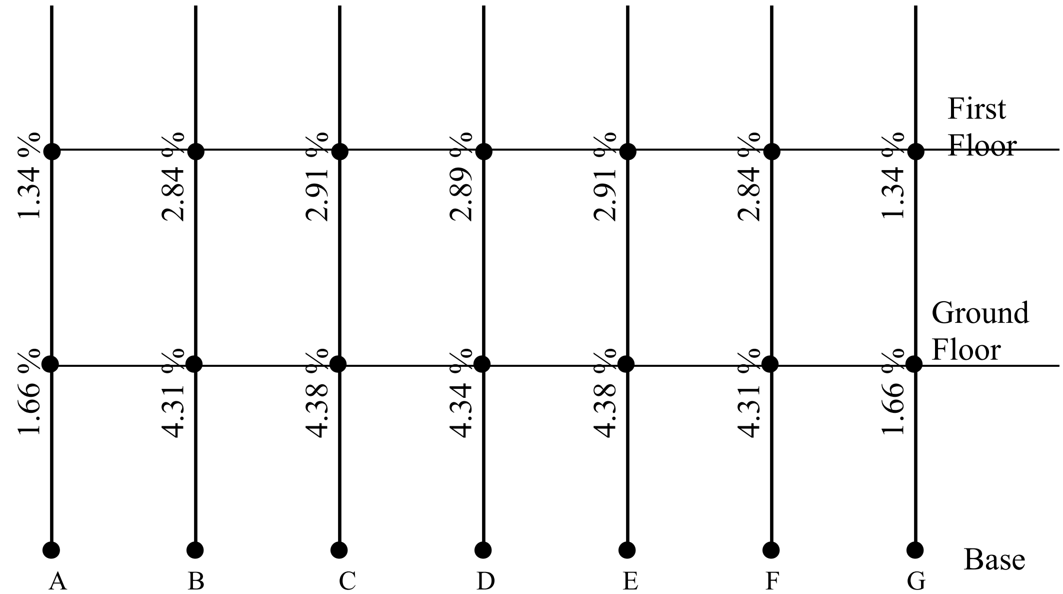


Figure 5 Integrated raft model (columns design) rebar ratio

there is a relatively more difference (upto 24%) in beams and column between discrete and integrated raft model. The difference in axial force in the columns ranges from 1 to 9%. More difference in axial force magnitude is observed at the 1st interior column. In integrated raft model, less moment magnitude M_{2-2} (about axis perpendicular to the applied lateral load) occurs at the column base because of partial fixity provided by the raft. However, this release at column base results in an increase of about 7% in the above stories. Exterior and 1st interior columns at base and above stories in integrated raft model show 20% less moment M_{3-3} (about local axis in the direction of applied lateral load) as compared to discrete model. However, other interior columns at base and in above stories draw more moment magnitude in integrated raft model.

The column design results for interior frame at grid 4 as shown in Fig. 1 for 1st two stories of discrete and integrated raft model are presented in Figs. 4 and 5. Exterior Columns show 24% less steel, whereas, all interior columns show 5% more steel in integrated raft model. This is because of the bowl shaped curvature of the raft due to which the flow of moment toward the centre of the raft takes place

Raft Moments: Raft moment decreases in case of integrated raft model as compared to discrete model as shown in tables 4 and 5.

Table 4: Raft Moment Mxx

Moment Mxx	Discrete Model	Integrated Model	%age Diff.
Max. +ve	230kN-m	198kN-m	14
Max. -ve	117kN-m	98kN-m	16

Table 5: Raft Moment Myy

Moment Myy	Discrete Model	Integrated Model	%age Diff.
Max. +ve	242kN-m	235kN-m	3
Max. -ve	120kN-m	107kN-m	10

Tables 4 and 5 indicate that the by integrated modeling of super structure and foundation, there is a flow of moment towards the superstructure and raft becomes lighter. It means superstructure bear some load of the raft and increases the stress and strain which decreases raft moment upto 16%.

Discrete and Integrated Strip Model: With the gravity load and lateral load combinations an increase in axial force in corner colu3mns and a decrease in the edge columns is observed. Maximum difference in axial force is about 10%. There is a release of moment M_{2-2} (about the local axis perpendicular to the applied lateral load) at the column base due to partial fixity provided by the strip, which results in an increase of moment upto 18% at the first story columns. Moment M_{3-3} (about local axis in the direction of applied lateral load), corner and 1st interior (edge column) columns at the base and above stories in integrated strip model show 20% less moment as compared to discrete model. However, in integrated strip model other interior columns (exterior edge columns) at base and in above stories attract more moment magnitude as in integrated raft.

The columns for the bottom two stories at grid 1 as shown in Fig. 2 are presented in Figs. 6 and 7 for the discrete and integrated strip model respectively. The design results of columns show 7% increase in reinforcement in integrated strip model as compared to discrete one.

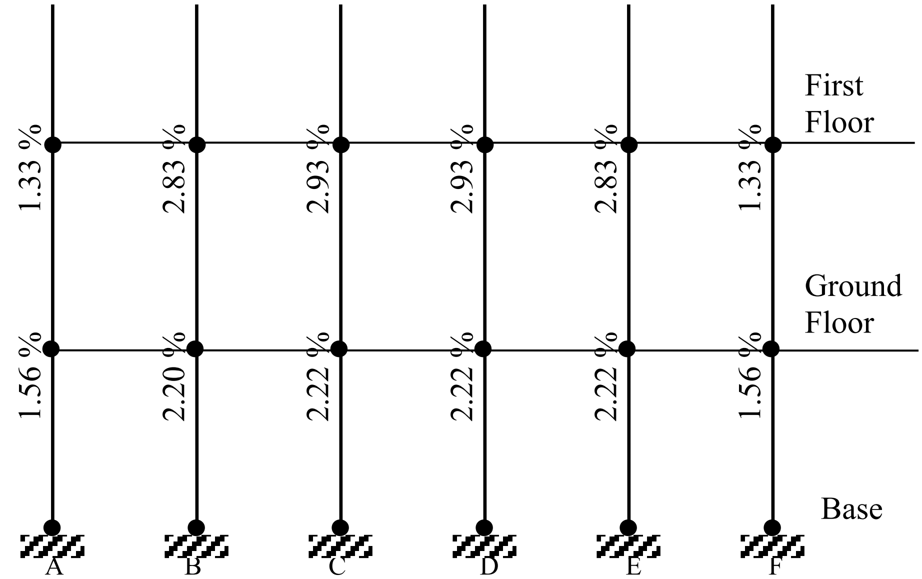


Figure 6. Discrete model (column design rebar ratio)

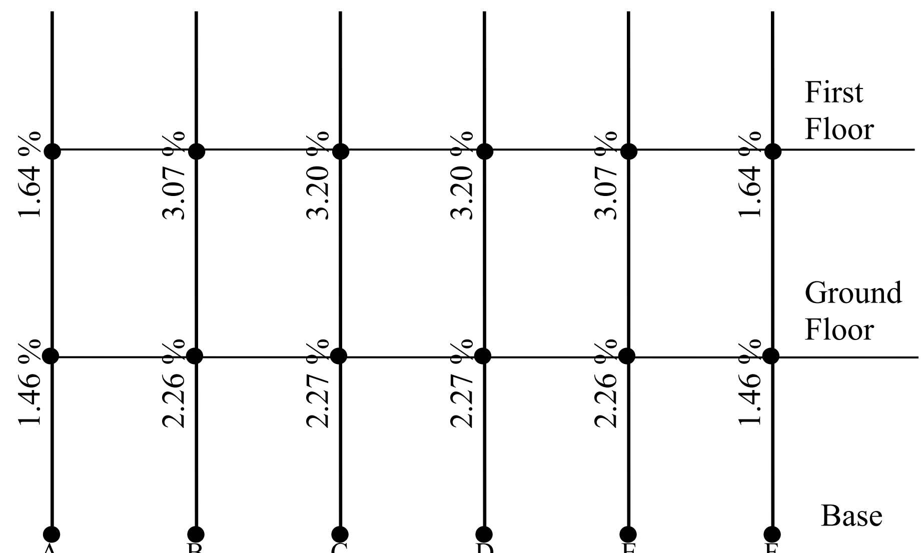


Figure 7. Integrated strip model (column design rebar ratio)

A B C D E F

567 174 481 | 506 139 472 | 467 138 467 | 472 139 506 | 481 174 567

414 209 431 | 409 204 377 | 374 197 374 | 377 204 409 | 431 209 414 First Floor

695 209 624 | 623 176 626 | 625 177 625 | 626 176 623 | 624 209 695

544 230 545 | 521 209 525 | 527 209 527 | 525 209 521 | 545 230 544 Ground Floor

Figure 8. Discrete model (beam design steel area in mm^2)

A B C D E F

725 209 544 | 666 184 616 | 656 186 656 | 616 184 666 | 544 209 725

489 209 549 | 525 209 555 | 557 209 557 | 555 209 525 | 549 209 489 First Floor

695 209 539 | 655 178 597 | 641 178 641 | 597 178 655 | 539 209 695

491 214 526 | 501 209 534 | 535 209 535 | 534 209 501 | 526 214 491 Ground Floor

Figure 9. Integrated strip model (beam design steel area in mm^2)

Strip Footing Moments: Strip moments M_{xx} and M_{yy} are relatively less in integrated strip model on Grid 1-B and 1-C as compared to discrete model as shown in Tables 6 and 7. However, on Grid 1-A integrated strip footing moments are relatively more than discrete model.

Table 6 Strip Moment M_{xx}

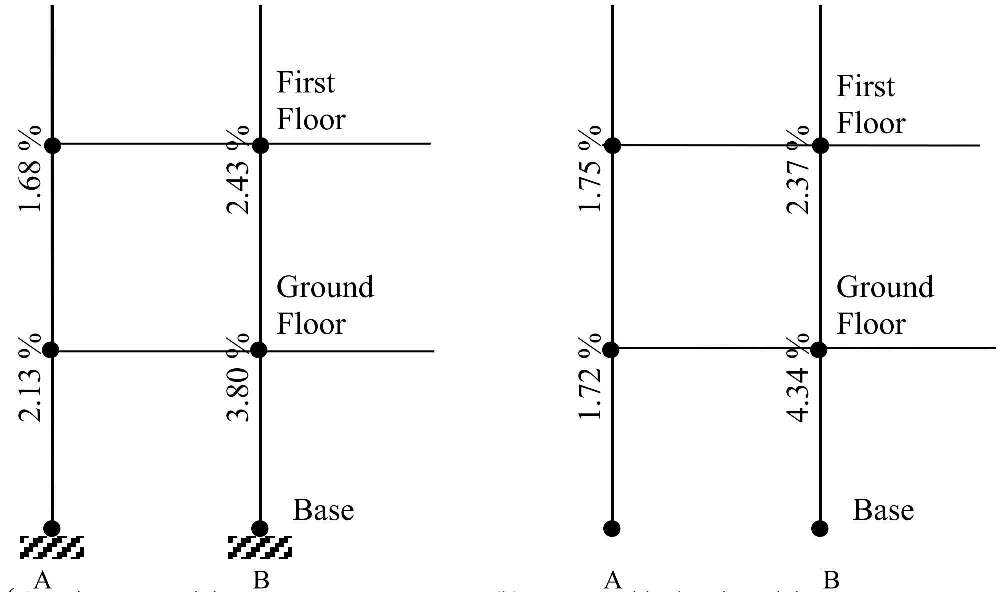
Footing Location	Discrete Model (kN-m)	Integrated Model (kN-m)	%age Diff.
Grid 1-A	142	160	11.2
Grid 1-B	380	368	3.10
Grid 1-C	351	350	0.0

Discrete and Integrated Isolated Footing Models: Detailed investigation of these models showed that column with large footing area attracts more moments at column base and hence results in more reinforcement ratio. With the increase in the area of foundation, the columns with large footing size demands more steel. In interior columns reinforcement ratio increases while in exterior columns it decreases in integrated modeling as compared to discrete model.

Table 7 Strip Moment M_{yy}

Footing Location	Discrete Model (kN-m)	Integrated Model (kN-m)	%age Diff.
Grid 1-A	190	207	8.20
Grid 1-B	393	382	2.70
Grid 1-C	401	397	1.0

The edge column on Grid 2A showed in Fig. 3 display 19% more reinforcement and the 1st interior column on Grid 2B show 13% less reinforcement in discrete model as compared to integrated isolated footing model as shown in Fig. 10.



(a) Discrete model (b) Integrated isolated model

Figure 10 Discrete and integrated model column design rebar ratio

Almost all beams showed less reinforcement in discrete model as compared to integrated isolated footing model. Reinforcement area of 1st floor beams on Grid 4 for discrete and integrated isolated footing model are presented in Figs. 11 and 12.

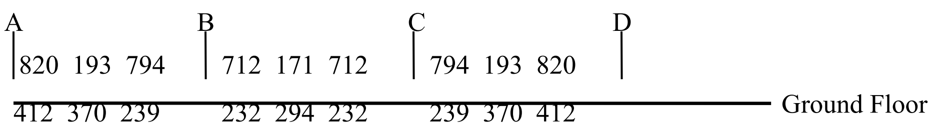


Figure 11 Discrete model (beam design steel area in mm^2)

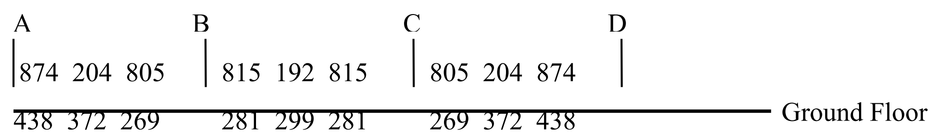


Figure 12 Integrated isolated footing model (beam design steel area in mm^2)

Isolated Footing Moments: Table 8 indicates less footing moment on Grid 2A on isolated footing of discrete model. However, integrated model reveals less moment magnitude on Grid 2B.

Table 8 Isolated footing moments M_{xx} & M_{yy}

Footing Location	Discrete Model (kN-m)	Integrated Model (kN-m)	%age Diff.
Grid 2A	86	101	14
Grid 2B	224	182	19

Unequal advancement spans with raft foundation: A hypothetical six storey six bays reinforced concrete building model is selected for study with 1.8m and 5.5m alternate spans in x and y direction. The building has a typical storey height of 3.65m.

The column design results for interior frame at grid 4 for the first two stories are presented in Figs.13 and 14. With the lateral plus gravity load combination, reinforcement area percentage difference between discrete and integrated raft models approaches almost 30% in interior columns. In interior columns design revealed more percentage of steel in integrated raft model.

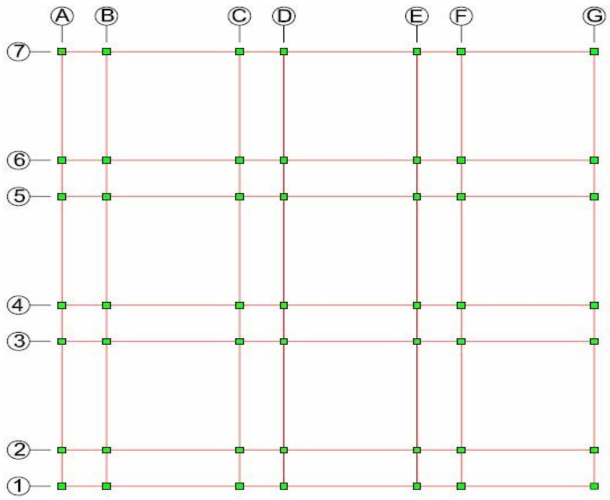


Figure 12A **Plan for discrete and integrated raft with unequal adjacent spans**

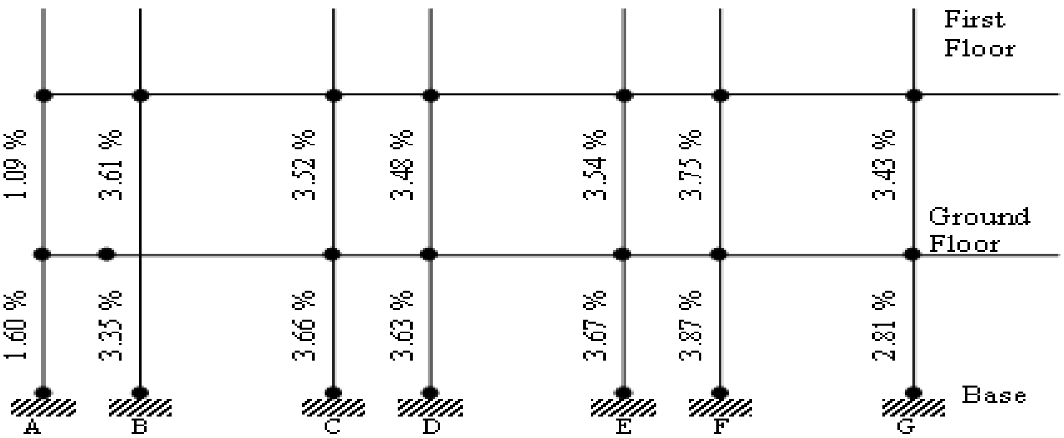


Figure 13 **discrete models (column design rebar ratio)**

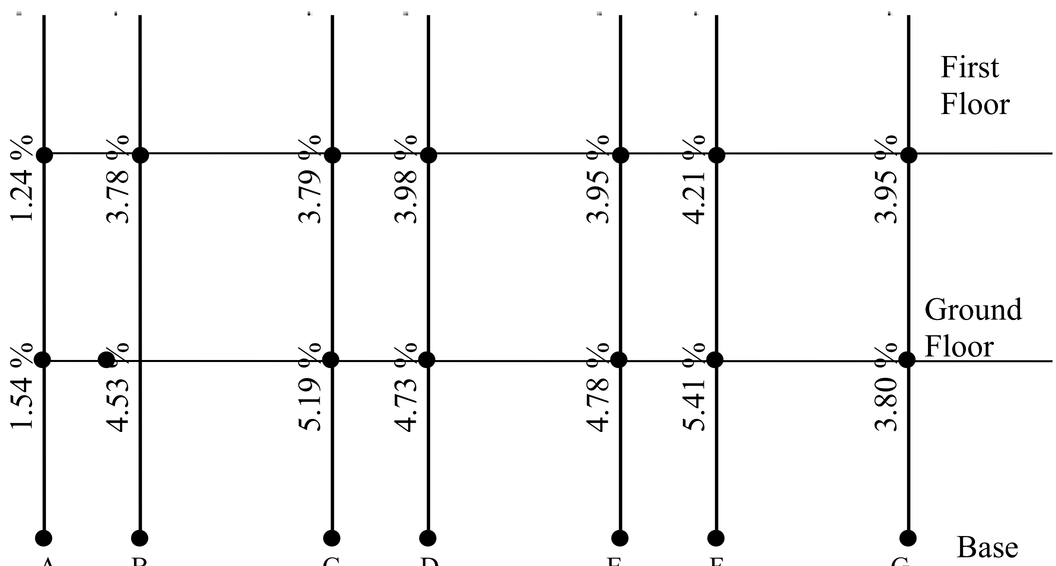


Figure 14. Integrated raft footing model (column design rebar ratio)

Sensitivity Analysis: To determine the effect of spring stiffness and footing thickness on superstructure response, design is compared by varying the spring and bending stiffness.

Spring Stiffness: Increase in spring stiffness while keeping bending stiffness of the footing constant affects the column design results. Since, with increase in spring stiffness differential and overall settlement decreases and becomes more uniform under the columns. Therefore, columns design result show close agreement with discrete model. But this happens at very high hypothetical value of spring stiffness which may practically occur only on rock. This observation is valid for all the cases of integrated footings studied.

Bending Stiffness: Increase in foundation thickness, while keeping the spring stiffness constant, also affects the superstructure design. By increasing thickness bending stiffness of the foundation increases which provides relatively more fixity to the columns at the base. Therefore, column design results show good agreement with discrete model. However, this agreement is seen more obvious in integrated raft and at very unusual thickness. With increase in thickness, integrated strip and isolated footing columns result showed little or no similarity to that of discrete model. This is due to the reason that strip footing behavior is just like a continuous beam and isolated footings act independent to each other.

Linear time history analysis: For linear time history analysis north south component of El Centro, Imperial Valley, USA earthquake of 1940 from PEER Strong Motion database is used. The linear time history analysis has been done only for discrete and integrated raft model. Linear time history is selected for comparative study as for Zone 2A the acceleration demand on the structure will be small and resultantly structure will remain nearly in the elastic range. 5% of the critical damping is assumed for the superstructure while damping in the foundation is ignored. However, integrated raft model showed more fundamental period because of the raft weight and springs as shown in table 9.

Table 9 Modal time periods of the buildings

Model	Mode	Period (Sec)	Modal Mass (%) U_x	Modal Mass (%) U_y
Discrete	1	1.564757	0.4525	83.925
	2	1.564757	83.925	0.4525
Integrated Raft	1	1.823447	0	80.5604
	2	1.823446	80.5603	0

The time at which peak displacement and peak acceleration occurred at the top story is delayed in integrated raft model as shown in table 10. The peak displacement increases and peak acceleration decreases at the top story in integrated raft model.

Table 10. Relative displacement and acceleration at top

Model	Time (Sec)	Displacement (Mm)	Time (Sec)	Acceleration (M/Sec^2)
Discrete	6.16	151.79	2.02	6.40
Integrated	11.9	178.72	9.06	4.26

The peak displacement in integrated raft model increases because the raft is modeled with spring which results in small lateral displacement at the column base so the absolute displacement at the roof increases. The decrease in peak acceleration is due to increase in fundamental period of the integrated model. Since, for long period structures acceleration response is relatively less as compared to short period structures. Lengthening of the period of the system and increased damping at the foundation due to soil foundation interaction will result in smaller design acceleration values when applying the code spectra (Stewart et al. 2003).

Ground displacement and acceleration at base: Ground displacement or ground acceleration at the column base is actually the input ground displacement or ground acceleration. In discrete model ground displacement or ground acceleration at the column base is exactly equal to input EL-Centro ground motion because of the fix base of columns. However, the observed displacement and acceleration at the column base is different from input ground motion because of the soil springs under the integrated raft.

The design results in integrated super and substructure raft model reveals more steel than discrete superstructure model. This increase in superstructure steel in integrated raft model reveals that it is probable that in spite of less acceleration magnitude as compared to discrete model release of moment from the raft resulted in an increase of moment in the superstructure. It has also been identified by Gazetas and Mylonakis (1998) and Mylonakis *et al*. (2006) that the lengthening of the period of a structure can lead to an increase in response during certain seismic events. Since, the response is more affected by the fundamental period of the system and dominant frequency of ground motion.
However, comparison of substructure design in the absence of time history results of discrete model response cannot be made. It can be inferred from superstructure results that raft design in integrated model will result in less percentage of steel as compared to discrete model.

Conclusions: From the comparative study on the seismic analysis of integrated and discrete super and substructure building systems following conclusions can be drawn

1. The exterior columns are with 23% more steel and all interior columns are with 5% less steel requirement in integrated super and substructure raft model as compared to discrete superstructure model. This difference is more obvious in the bottom two stories. Raft moment decreases by

about 16% in integrated super and substructure models.

2. Column results in integrated super and substructure models show good agreement with discrete superstructure models when spring stiffness is increased. With the increase in spring stiffness differential and absolute settlement under the columns decrease. Hence, integrated modeling will yield larger difference in results from discrete modeling when footings on soils of less bearing capacity are modeled.
3. Columns steel increases by about 7% in integrated super and substructure strip model as compared to discrete model and more obviously in the first floor.
4. Most of the beams show less reinforcement in discrete superstructure model as compared to integrated super and substructure strip model.
5. The moments in the strip footing in integrated model is less as compared to discrete model and the difference is upto 10%.
6. The exterior columns show 19% less steel and interior columns 13% more in integrated super and substructure isolated footing model as compared to discrete superstructure model.
7. There is about 19% decrease in the moments of isolated footings in integrated model as compared to discrete model.

Hence, for more realistic and safe structural design, it is realized that the integration between super and substructure should be taken into consideration.

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