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QUANTITY AND COST MODELLING OF FOUNDATIONS FOR 12 TO 20 STOREY RCC BUILDINGS DESIGNED FOR SEISMIC RESISTANCE

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Abstract

This paper presents the quantity assessment of the structural materials and cost prediction of building foundation systems of 12 to 20 storeyed reinforced concrete buildings designed for seismic resistance in low, moderate and high seismic zones of India. Earlier work on this aspect has been carried out for the foundation systems of 2 to 10 storeyed buildings [1]. The work on this theme has also been carried out for the superstructure structural components of the buildings [2]. The superstructure framing system of the buildings studied consists of moment resisting frames in combination with shear walls.The foundation system of the buildings,depending upon the variation in the parameters considered,comes under one of the following three types; isolated/strip footing, raft foundation and pile foundation. Considering four seismic hazard levels, five building heights and four allowable bearing pressure values of soils, the resulting eighty cases of foundation designs are carried out as per the Indian building codes and the quantity estimation of structural materials; structural concrete, steel reinforcement and shuttering are determined following the standard quantity surveying methods. The requirement of the structural materials and the foundation costs are expressed per unit gross floor area of the buildings to provide the desired quantity and cost modelling of the foundation systems under the considered parametric variations including the cost premium for providing the different levels of seismic resistance.

Depending upon the parametric variations,the cost range for the isolated footings,raft and pile foundations works out to Indian rupees 930 to 1260,1500 to 2000 and 2500 to 3700 per sqm of the building floor área respectively.The cost premium for providing seismic resistance for the foundation types ranges between 5 to 35% for moderate to high seismic zones as detailed out in the results of the study.

The present work contributes to the knowledge area of building economics with reference to building foundations designed for different levels of seismic hazards. The results of the study are useful for the design professionals for the selection of foundation types in the early stage design development and for the construction managers for project costing,scheduling and material mangement applications.

KEYWORDS: *Reinforced concrete buildings; foundations; seismic resistance; quantity model; cost model*

1. Introduction

Building foundation as an interface structural component, perform the function of safely transmitting the building loads including the wind and earthquake effects to the supporting soil strata without its shear and settlement related failures. The earthquake loads induce increased and uneven soil pressures causing differential settlements and overturning effects on the foundations. Considering these aspects, appropriate foundation system is selected, and structural design of the foundation elements are carried out for resisting the induced loads and moments. The central idea of this work is to bring out the design implication in the foundation systems in terms of the requirement of structural materials and resulting cost of the foundation systems considering the variations in the building loads, soil parameters and seismic hazard levels. Towards this objective, quantity and cost modelling of three commonly adopted foundation systems are developed and presented in this work accounting the variations in these influencing parameters.

2. Cost Aspects of Building Foundation

The foundation systems of the multi-storeyed buildings constitute one of the major cost components of the overall building cost. Although the cost of building foundations is primarily dictated by the building structural systems, loads, soil and site conditions, the effect of these parameters appears to have not been quantified and reported in the literatures. Most of the cost estimation approaches are approximate and derived from the experiences of the constructed projects. Also, the cost implications for incorporating various levels of seismic resistance in building foundations under different soil conditions is a much less understood aspect although some studies are available on the cost premium for providing earthquake resistance for superstructure systems. In an earlier study by the authors [1], a parametric cost estimation approach for the foundations of 2 to 10 storeyed buildings is presented considering the variations in the allowable bearing pressure of soils and different levels of seismic effects. This paper presents the quantity assessment of the structural materials and cost prediction of foundation systems of 12 to 20 storeyed reinforced concrete buildings designed for seismic resistance in low, moderate and high seismic zones of India.

3. Buildings Studied

3.1. Superstructure

The proposed quantity and cost modelling aspects are studied for the foundation systems of five reinforced concrete buildings (12, 14, 16, 18 and 20 storeyed). The structural system adopted is with moment resisting frames in combination with shear walls. The structural framing consists of 6m span three bay frames spaced at 6.5m centre to center, a commonly adopted structural system for office buildings in India Fig.1. The floor system is with 120mm thick solid slabs supported on main and secondary beams. The column sizes adopted vary from 800x800mm to 500x500mmm depending upon the building heights and the shear wall thickness varying from 350mm to 250mm. The main and secondary beam sizes adopted are 350 mmX650 mm and 250 mmX450 mm respectively.

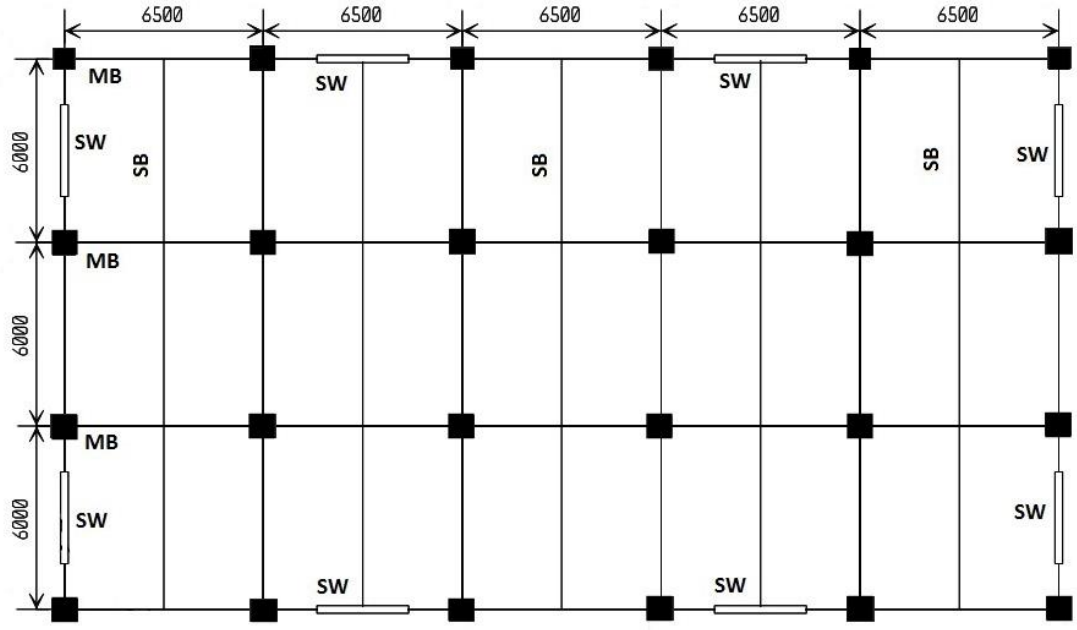

Fig. 1 - Superstructure framing plan at typical floor

3.2 Foundation systems

The selection of the foundation systems for the building heights considered in this study come under one of the following types; isolated/strip footings, raft foundation covering the entire footprint of the building and pile foundation transmitting the loads to a deeper competent stratum. For determining the foundation type, the support reactions from the seismic analysis of the buildings for all the four seismic zone conditions are compiled in the form of load/moment charts (LMCs) and for four soil conditions with ABP values 150 KN/sqm to 300 KN/sqm the foundation types are worked out and shown in Table 1. Pile foundations are provided for buildings wherein shallow foundations are not feasible. In the higher seismic zones, the foundation type changes due to the increased seismic loads/moments in the foundations. With the introduction of below ground basement floors, the foundation type may change into a lower category due to the advantage of increase in ABP values on account of the weight of the soil removed. However, such building cases with basement storeys are not considered in the present study.

Table 1 - Foundation systems selected for the case study buildings

No of storeys	Seismic Zone	Allowable bearing pressure of soils ABP (KN/m^2)				
		100	150	200	250	300
12	NS	P	P	R	I/S	I/S
	II	P	P	R	I/S	I/S
	III	P	P	R	I/S	I/S
	IV	P	P	R	I/S	I/S
	V	P	P	P	R	I/S
14	NS	P	P	P	R	I/S
	II	P	P	P	R	I/S
	III	P	P	P	R	I/S
	IV	P	P	P	R	I/S
	V	P	P	P	R	R
16	NS	P	P	P	R	I/S
	II	P	P	P	R	I/S
	III	P	P	P	R	R
	IV	P	P	P	P	R
	V	P	P	P	P	R
18	NS	P	P	P	P	R
	II	P	P	P	P	R
	III	P	P	P	P	R
	IV	P	P	P	P	R
	V	P	P	P	P	P
20	NS	P	P	P	P	R
	II	P	P	P	P	R
	III	P	P	P	P	R
	IV	P	P	P	P	P
	V	P	P	P	P	P

Foundation types: P-Pile, R-Raft, I/S- Isolated/strip footings

4. Seismic Effects Considered

The effect of different levels of seismic forces on the foundation systems of the case study buildings are studied by considering them located in four different seismic zones of India as per Indian Standard IS 1893: 2016 [3]. Each seismic zone is assigned with a seismic zone factor characterizing the maximum peak ground

acceleration that can occur in the maximum considered earthquake (MCE) in the zone. The seismic parameters of the Indian seismic zones are shown in Table 2.

Table 2 – Seismic parameters of Indian seismic zones

Seismic Zone	Zone Factor (Z)	Design peak ground accelerations	Seismic intensity (MSK 64) scale
II Low seismic zone	0.10	0.05g	VI or less
III Moderate seismic zone	0.16	0.08g	VII
IV Severe seismic zone	0.24	0.12g	VIII
V Very severe seismic zone	0.36	0.18g	IX

5. Seismic Analysis and Design

Earthquake analysis are carried out on the three-dimensional space frame model of the buildings. The buildings being simple and of regular configurations, equivalent static load approach was adopted for the determination of the seismic forces. For the design of the foundation systems, the column support reactions in the form of load-moment charts are generated for the specified load combinations of gravity and seismic loads. Based on these loads and moments transmitted to foundations and with the knowledge of the allowable bearing pressure of soils, the type of foundations is decided, and their structural designs and reinforced detailing were carried out in accordance with the Indian codes of practice [4]. The bill of quantities of the foundation elements are worked out to arrive at the proposed quantity and cost modeling of the foundation systems.

6. Quantities and Cost Modelling of Building Foundations

The quantity modelling of building foundations expresses the quantities of structural concrete, reinforcement steel and shuttering materials for the foundation elements as quantities required per sq.m of the floor area of the building and the corresponding foundation structural costs per sq.m. are determined with the prevailing unit rates of construction of these quantities [5]. For the buildings with isolated/strip footings, the foundation elements considered are the footings, pedestals and grade beams connecting the columns near the ground level. For raft foundations, raft slab of uniform thickness covering the entire footprint of the building with column pedestals are considered along with the grade beams near the ground level. For the pile foundations, piles, pile caps with pedestals and the tie beams connecting the pile caps are considered. In all the above cases the quantities of the column portion below the ground level up to the top of pedestal including the anchorage length of column reinforcement inside the foundation is also considered. The proposed quantity and cost model for the three types of foundations considers the variability in the three influencing parameters; number of storeys, allowable bearing pressure of soils and the seismic hazard levels defined by the seismic zones and brings out the cost implications on account of these parameters.

6.1 Quantity and Cost modelling of Foundations with Isolated Footings

The structural quantities of isolated footings system with connecting grade beams are expressed in terms of quantities per sqm floor area of the buildings for different seismic zones and ABP values are shown in Table 3. The corresponding structural costs are shown in Table 4, along with the percentage increase in cost to resist the seismic effects in higher seismic zones. The variation in structural quantities could be observed with the variation in the three parameters. The requirement of structural concrete varies from 0.60 to 0.08 cum and the steel reinforcement varies from 2.70 to 4.90 kg per sqm of floor area. The foundation cost varies between Rupees 930 to 1260 per sqm of the floor area. The percentage cost increase in seismic zone III, IV and V over non-seismic condition may be broadly taken as 5%, 20% and 30% respectively.

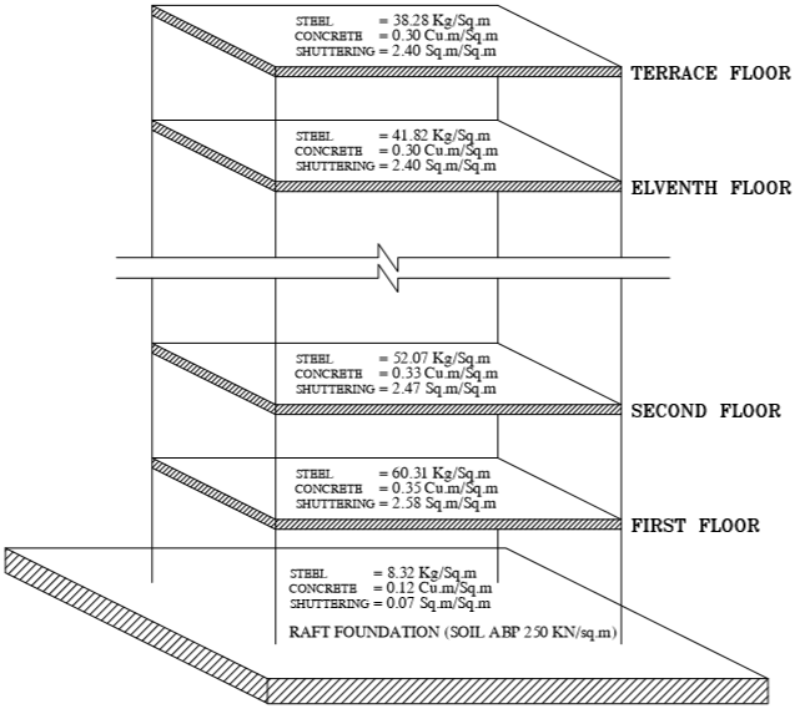

Fig. 2 - Quantity model for the 12 storeyed building with raft foundation in seismic zone **V**

Table 3 - Foundations with Isolated footings: Structural quantities per sq.m of floor area

No of storeys	ABP KN/m^2	Non-seismic zone			Zone II			Zone III			Zone IV			Zone V		
		Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2
12	250	0.07	3.42	0.08	0.08	3.41	0.07	0.07	3.58	0.08	0.08	4.89	0.08	Raft		
	300	0.06	2.70	0.08	0.06	3.41	0.08	0.06	3.43	0.08	0.07	3.56	0.08	0.07	4.80	0.08
14	300	0.07	3.20	0.07	0.07	3.20	0.07	0.08	3.65	0.08	0.08	4.39	0.08			
16	300	0.08	3.59	0.07	0.08	3.59	0.07	Raft			Raft			Raft		

Table 4 - Isolated Footings: Structural cost and Cost premium for Seismic effects

Building	ABP KN/m^2	Cost in Rupees/m^2 of floor					% Increase over Non seismic case			
		NS Zone	Zone II	Zone III	Zone IV	Zone V	Zone II	Zone III	Zone IV	Zone V
12 storeyed	250	1063	1063	1112	1261	Raft	Nil	5%	19%	-
	300	930	930	970	1040	1214	Nil	4%	12%	30%
14 storeyed	300	1011	1011	1132	1237	Raft	Nil	2%	22%	-
16 storeyed	300	1114	1114	Raft	Raft	Raft	Nil	-	-	-

6.2. Quantity and Cost modeling of raft Foundations

The building cases for which raft foundations are applicable are shown in table 1. The type of raft considered is of reinforced concrete mat of uniform thickness covering the entire footprint of the building with projections from the outer edge peripheral columns/shear walls. The column/shear wall bases are provided with pedestals at their junction with the raft to improve the punching shear resistance. A set of beams connecting these vertical elements are provided at the plinth level to reduce the slenderness of the columns and to support the non-structural walls of the ground storey.

The design thicknesses of the raft vary from 1.0 m to 1.60 m for the 12 to 20 storeyed buildings. The raft analysis for various seismic zone conditions are carried out by modelling the raft with beam analogy. Based on the structural designs carried out, the structural quantities are determined for all the building cases considered in each of the seismic zones and the corresponding structural costs are worked out per sqm of the floor area. The requirement of structural quantities which includes the quantities of grade beams and columns/shear walls below plinth level are presented in table 5, and the cost and cost premium is shown in table 6.

The concrete quantity varies from 0.10 to 0.13 cum/sqm and the steel reinforcement varies in the range of 5.90 to 8.30 Kg/sqm depending upon the number of storeys, soil ABP values and the seismic zones. Lower values of these quantity requirements are associated with higher ABPs in lower seismic zones with increased floor area supported by the foundation. The foundation costs, depending on the parameters, are in the range of Rupees 1500 to 2000/sqm. The cost premium for incorporating the seismic resistance could be broadly taken as 10%, 15% and 20% for Seismic Zone III, IV and V over non-seismic condition respectively. Another improved analysis procedure is being done with the combined modelling of the superstructure and foundation with raft considered as plate elements resting on the soil modelled as elastic springs using the modulus of subgrade reaction property of the soil.

Table 5 - Raft Foundation: Requirement of structural quantities per sqm of floor area

No of storeys	ABP KN/m^2	Non-seismic zone			Zone II			Zone III			Zone IV			Zone V		
		Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2	Concrete m^3	steel kg	Shuttering m^2
12	200	0.11	6.91	0.07	0.12	6.97	0.07	0.12	7.81	0.07	0.13	8.30	0.08	Pile		
	250	I/S			I/S			I/S			I/S			0.12	8.32	0.07
14	250	0.11	6.39	0.06	0.11	6.40	0.06	0.11	7.11	0.07	0.11	7.52	0.07	0.12	8.32	0.07
	300	I/S			I/S			I/S			I/S			0.11	7.40	0.06
16	250	0.11	6.66	0.06	0.11	6.66	0.06	0.12	7.22	0.06	Pile			Pile		
	300	I/S			I/S			0.11	6.16	0.06	0.10	6.72	0.06	0.11	7.56	0.06
18	300	0.10	5.90	0.05	0.01	5.90	0.05	0.10	6.43	0.05	0.11	6.97	0.05	Pile		
20	300	0.10	6.02	0.05	0.10	5.97	0.05	0.10	6.47	0.05	Pile			Pile		

Table 6 - Raft Foundations: Structural cost and premium for seismic effects

Building	ABP KN/m^2	Cost in Rupees/m^2 of floor area					Increase in cost over NS Zone			
		Zone NS	Zone II	Zone III	Zone IV	Zone V	Zone II	Zone III	Zone IV	Zone V
12 storeyed	200	1782	1782	1951	2043	Pile	-	9%	15%	-
	250	I/S	I/S	I/S	I/S	1943	-	-	-	-
14 storeyed	250	1644	1644	1774	1823	1978	-	8%	11%	20%
	300	I/S	I/S	IS	I/S	1732	-	-	-	-
16 storeyed	250	1709	1709	1792	Pile	Pile	-	5%	-	-
	300	I/S	I/S	1508	1632	1785				
18 storeyed	300	1510	1510	1581	1703	Pile	-	5%	13%	-
20 storeyed	300	1542	1542	1605	Pile	Pile	-	4%	-	-

6.3. Quantity and Cost modelling of Pile Foundations

Pile foundations are considered for the 12 to 20 storeyed buildings for which shallow foundations are not feasible due to lower ABP values. Based on the prevailing construction practice, 20-meter-long bored cast-in-situ piles of 600, 750, 1000- and 1200-mm diameter are adopted with their respective safe vertical load capacities as 150,200,300 and 380 tons. These pile capacities have larger frictional component compared end bearing resistance. This representative pile system selection is done based the geotechnical investigation reports of constructed buildings in this range. The soil type is predominately silty sand with negligible cohesion and angle of shearing resistance varying between 25 to 30 degrees. Considering the load/moment values of the support reactions of the superstructure and pile capacities, the pile configurations supporting the columns and shear walls through pile caps are worked out for all building cases in the four seismic zones. The permissible 25% increase in pile capacities are allowed under seismic conditions. The pile group configuration adopted for the 16-storey building case in seismic zone IV is shown in Fig.3.

The structural design of the piles and pile caps are designed in accordance with the provisions of the codes of the Bureau of Indian Standards. The top portion of the piles, using the equivalent cantilever approach, are designed to resist to lateral loads induced due to the building seismic base shear and extra reinforcements where required are provided in addition to the minimum longitudinal reinforcement percentage of 0.40% of the pile section. This extra reinforcement increases with increase in base shear in higher seismic zones. The characteristic strength of concrete adopted for piles and pile caps with connecting tie beams are M30 and M25 grade respectively. The steel reinforcement is of Fe500 grade.

The structural designs and detailing of the pile foundation systems are worked out for all the five building heights under four seismic zone conditions. The total quantities of structural concrete, steel reinforcement and shuttering are determined for all the components of the piling work following the standard quantity surveying practice. These required structural quantities are then expressed per sqm of the total floor area of the building thus providing the desired quantity modelling of the pile foundations and shown in table 7. The quantity modelling results arrived here are for the pile foundation designs worked out with piles of specified length, diameter and capacities in the considered soil conditions. The results of the quantity modelling would vary with the variation in soil conditions with pile capacities and their configurations. However, the presented quantity modelling is considered to broadly represent for the buildings in similar soil conditions.

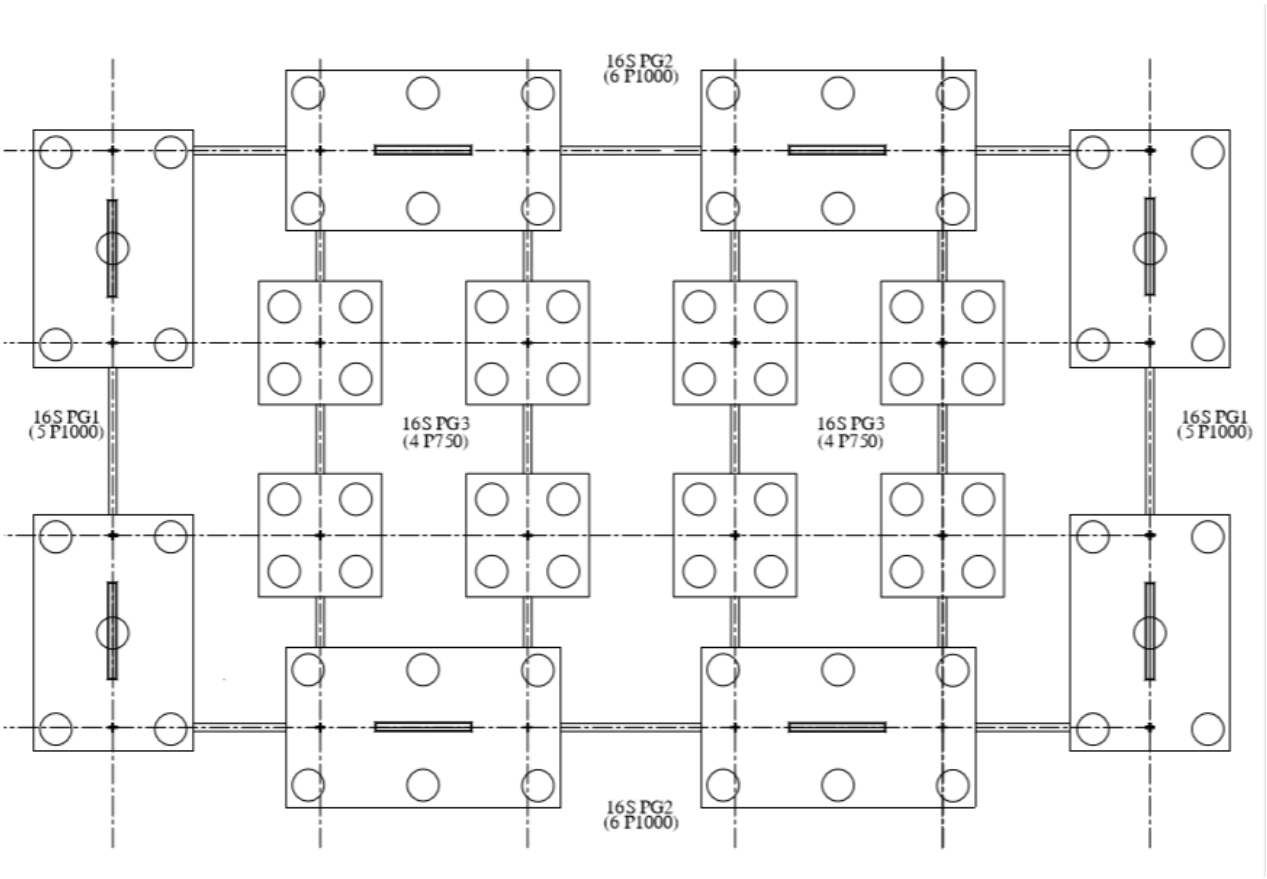

Fig. 3- Pile layout plan for 16 storeyed building in seismic Zone IV.

Based on the structural quantities determined in the quantity modelling process, the structural costs for the two components of the pile foundation works are worked out using the construction cost data for pile foundation works available in the standard schedule of rates [5]. The rates for pile installation include making bores with bentonite slurry process and tremie concreting. The cost of pile reinforcement is considered separately. The pile foundation costs are determined for the building cases in different seismic zones and the corresponding costs per sqm of the floor area arrived are also shown in Table 7.

For the considered parametric variations, for the pile caps with tie beams, the requirement of concrete quantities and steel reinforcement ranges from 0.03 to 0.06 cum and 1.89 to 3.79 Kg per sqm of floor area respectively. For the pile component, the corresponding values are 0.09 to 0.13 cum and 4.37 to 7.00 kg per sqm of the floor area of the building. The foundation cost variation is around Rupees 2500 to 3700 per sqm of the floor area. The premium for incorporating earthquake resistance in seismic zone III IV and V over non seismic case may be considered broadly around 10%, 20% and 35% respectively. In zone II seismic situation, non-seismic design governs the design with cost for zone II same as non-seismic case

Table 7 - Pile Foundations: Structural quantities and cost per sqm of floor area and cost premium

No of storeys	Seismic Zone	Pile caps and Tie beams				Piles			Total cost / sqm	% increase in cost over NS
		Concrete m^3/m^2	Steel kg/m^2	Shuttering m^2/m^2	Cost/ m^2 (Rs)	Concrete m^3/m^2	Steel kg/m^2	Cost/ m^2 (Rs)		
12	NS	0.03	1.89	0.06	533	0.09	4.44	1931	2464	-
	II	0.03	1.89	0.06	533	0.09	4.44	1931	2464	-
	III	0.04	2.49	0.06	684	0.09	4.62	1876	2560	4%
	IV	0.05	2.80	0.07	785	0.10	5.47	2153	2938	19%
	V	0.06	3.49	0.07	914	0.11	6.20	2417	3331	35%
14	NS	0.04	1.91	0.05	546	0.10	4.53	2083	2629	-
	II	0.04	1.91	0.05	546	0.10	4.53	2083	2629	-
	III	0.04	2.53	0.06	698	0.12	5.33	2333	3031	15%
	IV	0.05	2.83	0.06	817	0.12	5.83	2392	3209	22%
	V	0.06	3.57	0.07	974	0.12	6.18	2539	3513	34%
16	NS	0.04	2.14	0.05	657	0.11	4.46	2100	2757	-
	II	0.04	2.14	0.05	657	0.11	4.46	2100	2757	-
	III	0.05	2.56	0.06	738	0.11	4.91	2152	2890	5%
	IV	0.05	2.87	0.06	841	0.11	5.70	2335	3176	15%
	V	0.06	3.61	0.07	994	0.12	6.25	2458	3452	25%
18	NS	0.04	2.19	0.05	646	0.09	4.41	2012	2658	-
	II	0.04	2.19	0.05	646	0.09	4.41	2012	2658	-
	III	0.05	2.59	0.05	747	0.10	4.60	2018	2765	4%
	IV	0.05	2.90	0.06	787	0.11	5.34	2152	2939	11%
	V	0.06	3.68	0.06	1024	0.12	6.45	2438	3462	30%
20	NS	0.05	2.27	0.05	686	0.10	4.37	2060	2746	-
	II	0.05	2.27	0.05	686	0.10	4.37	2060	2746	-
	III	0.05	2.62	0.05	737	0.11	4.81	2110	2847	4%
	IV	0.06	3.08	0.05	896	0.12	5.93	2301	3197	16%
	V	0.06	3.79	0.06	994	0.13	7.00	2564	3558	30%

6.4 Cost comparison of foundation systems

The cost comparison between the three types of foundation systems for the five building heights considered with location in four seismic zones under different soil conditions characterised by their allowable bearing pressure (ABP) values are given in table (8). Variation in foundation cost for different soil ABP values and for different seismic zones is shown in Fig.4.

The change of foundation types could be observed due to these influencing parameters. For the given building height, depending upon the combination of these parameters, the cost of providing the raft foundation and pile foundation could be around 1.5 to 2 times and 2.5 to 3 times the cost of isolated/strip footing foundation respectively. It is also observed that in seismic zone II, non-seismic case could govern the design with the corresponding cost. The requirement of structural materials for zone II design may become less compared to non-seismic condition due to the permissible increase of soil and pile capacities under seismic conditions. However, in such situation the governing non-seismic design needs to be adopted for zone II with the corresponding cost.

Table 8 - Cost comparison of foundation systems under parametric variations

No. of storeys	Seismic Zone	Foundation costs in Rupees per sqm of floor area				
		ABP 100	ABP 150	ABP 200	ABP 250	ABP 300
12	NS	2464 (P)	2464 (P)	1782 (R)	1063(I/S)	930 (I/S)
	II	2464(P)	2464(P)	1782 (R)	1063(I/S)	930 (I/S)
	III	2560(P)	2560(P)	1951 (R)	1112 (I/S)	960 (I/S)
	IV	2938 (P)	2938 (P)	2043 (R)	1261 (I/S)	1040 (I/S)
	V	3331(P)	3331(P)	3331(P)	1943 (R)	1214 (I/S)
14	NS	2629(P)	2629(P)	2629(P)	1644(R)	1011 (I/S)
	II	2629 (P)	2629 (P)	2629 (P)	1644(R)	1011(I/S)
	III	3031(P)	3031(P)	3031(P)	1774(R)	1132 (I/S)
	IV	3209(P)	3209(P)	3209(P)	1823 (R)	1237 (I/S)
	V	3513 (P)	3513 (P)	3513 (P)	1978 (R)	1732 (R)
16	NS	2757 (P)	2757 (P)	2757 (P)	1709 (R)	1115 (I/S)
	II	2757 (P)	2757 (P)	2757 (P)	1709 (R)	1115 (I/S)
	III	2890 (P)	2890 (P)	2890 (P)	1792 (R)	1508 (R)
	IV	3176 (P)	3176 (P)	3176 (P)	3176 (P)	1632 (R)
	V	3452(P)	3452 (P)	3452 (P)	3452 (P)	1785 (R)
18	NS	2658 (P)	2658 (P)	2658 (P)	2658 (P)	1510(R)
	II	2658(P)	2658(P)	2658(P)	2658(P)	1510 (R)
	III	2765 (P)	2765 (P)	2765 (P)	2765 (P)	1581 (R)
	IV	2939 (P)	2939 (P)	2939 (P)	2939 (P)	1803 (R)
	V	3462 (P)	3462 (P)	3462 (P)	3462 (P)	3462(P)
20	NS	2746 (P)	2746 (P)	2746 (P)	2746 (P)	1542 (R)
	II	2746 (P)	2746 (P)	2746 (P)	2746 (P)	1542 (R)
	III	2847 (P)	2847 (P)	2847 (P)	2847 (P)	1605 (R)
	IV	3197 (P)	3197 (P)	3197 (P)	3197 (P)	3197 (P)
	V	3559 (P)	3559 (P)	3559 (P)	3559 (P)	3559 (P)

I/S- Isolated/strip footing, R-Raft foundation, P-Pile foundation

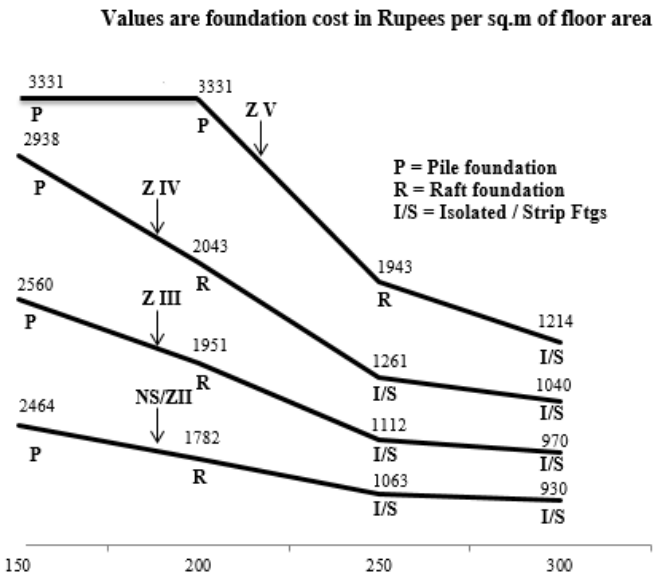

Fig. 4 – Variation in cost with foundation types (12 storey building)

7. Structural Quantities of Foundation in actual buildings

The structural quantities for some of the actual buildings constructed in different seismic zones of India are compiled and shown in Table 9, along with foundation types and soil parameters.

Table 9 - Structural quantities of Foundations in actual buildings (per sq.m floor area)

Building	Seismic Zone	Foundation	Concrete m^3/m^2	Steel kg/m^2
2 storeyed residences	II	Isolated Footing Soil ABP 250 KN/Sq.m.	0.08	6.31
3 storeyed residences	V	Isolated Footing Soil ABP 100 KN/Sq.m.	0.13	9.21
4 storeyed office	II	Isolated Footing Soil ABP 250 KN/Sq.m.	0.06	3.32
14 storeyed office	IV	Raft Foundation Soil ABP 200 KN/Sq.m.	0.12	12.59
8 storeyed residences	IV	Pile Foundation 500mm dia. 18m long piles	Pile Cap 0.06 Piles 0.14	Pile Cap 3.50 Piles 9.60
9 storeyed residences	IV	Pile Foundation 600mm dia. 18m long piles	Pile Cap 0.08 Piles 0.19	Pile Cap 5.20 Piles 10.70
11 storeyed residences	IV	Pile Foundation 500mm dia. 18m long piles	Pile Cap 0.08 Piles 0.18	Pile Cap 4.83 Piles 10.20
11 storeyed residences	III	Pile Foundation 600mm dia. 29m long piles	Pile Cap 0.07 Piles 0.25	Pile Cap 5.00 Piles 16.53

8. Results of the study

The results of the study are summarized as under;

i) The study provides the quantity and cost modelling of foundation systems of five reinforced concrete buildings (12, 14, 16, 18 and 20 storey) designed for four seismic hazard levels prescribed in the seismic zones of India. Through the quantity and cost modelling approach, the requirement of the quantities of the structural materials and the foundation costs are per unit floor area of the buildings (square meter costs) are predicted. Three types of building foundation mentioned below are considered incorporating the effect of variations in three influencing parameters; number of storeys, allowable bearing pressure of soils and the seismic hazard levels. The cost premium for providing seismic resistance over non-seismic conditions are quantified.

ii) For foundations with isolated/strip footings, depending upon the combination of the three parameters, the requirement of structural concrete and steel reinforcement varies between 0.06 to 0.08 cum and 2.70 to 4.90 kg per sqm of the floor area respectively. The foundation cost varies in the range of Rupees 930 to 1260 per sqm of the floor area. The cost premium for seismic resistance in seismic zone III, IV and V over non-seismic condition may be broadly taken as 5%, 20% and 30% respectively.

iii) For raft foundations, the requirement of structural concrete and steel reinforcement varies between 0.10 to 0.13cum and 5.90 to 8.30kg per sqm of the floor area respectively. The lower requirements are is associated with higher allowable bearing pressure of the soils in lower seismic zones. The foundation costs, depending on the parameters, are in the range of Rupees 1500 to 2000/sqm. The cost premium for providing seismic resistance may be broadly taken as 10%, 15% and 20% for zone III, IV and V over non-seismic condition.

iv) For pile foundations, depending on the buildings and their locations in seismic zones, the requirement of structural concrete and steel reinforcement for the pile caps varies between 0.03 to 0.06 cum and 1.90 to 3.80 kg per sqm of the floor area respectively. For the piling component, the requirement of tremie concrete and steel reinforcement varies between 0.09 to 0.13 cum and 4.37 to 7.00 kg per sqm of the floor area respectively. The pile foundation cost depending on the two parameters varies in the range of about Rupees 2500 to 3600 per sqm of the floor area. The cost premium for earthquake resistance in seismic zone III, IV and V over non seismic case may be considered broadly 10%, 20% and 35% respectively. In zone II seismic situation, non-seismic design governs the design with cost same as non-seismic case.

v) The relative cost comparison of the three type of foundations is made. For a given building with its associated loads, the requirement for the type of foundation would change from the simple isolated/strip footing to raft or to pile foundation depending upon the allowable bearing pressure of the soil. The cost of providing the raft foundation and pile foundation is around 1.5 to 2 times and 2.5 to 3 times the cost of isolated/strip footing foundation respectively. This brings out the need to determine the allowable soil bearing pressure values through careful geotechnical investigation of the sites to achieve safe and economical foundation systems.

9. Conclusions

The selection and design of the building foundations is governed by the building and supporting soil characteristics, wind and earthquake effects besides the site conditions. Although these parameters are recognised by the designers and considered in the design process, there is lack of documented information on the quantification of structural material requirements and associated cost implications due to the variability in these parameters. In this context, the present study has evolved the quantity and cost modelling of three types of foundation systems for reinforced concrete buildings considering the variations on number of storeys, allowable bearing pressure of soils and seismic hazard levels. The cost premium for incorporating the seismic resistances for different hazard levels are also brought out. Further studies are required to quantify the effects of different structural configurations, occupancy types, soil and site conditions and foundation types. Besides the seismic design process, the presented study is expected to be useful in the area of building economics and construction management applications.

10. References

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