COST MODELING OF FOUNDATIONS OF REINFORCED CONCRETE BUILDINGS DESIGNED FOR SEISMIC EFFECTS

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ABSTRACT

The paper presents the quantity and cost modeling of building foundations of reinforced concrete multistoreyed buildings in the range of two to ten storeys designed for seismic forces in the various seismic zones of Indian subcontinent and quantifies the cost premium for providing seismic resistance. The foundation types considered are; isolated footings, raft and pile foundations under different allowable bearing pressure values of the supporting soils. The study provides the requirement of structural quantities and foundation costs per unit floor area of the building in different seismic zones. The result of the study are useful for the design professionals and cost engineers during early stages of design development and cost planning. The study also highlights the achievable economy in foundation costs through proper evaluation of allowable bearing pressure of soils through adequate geotechnical investigations of the building sites.

KEYWORDS: Reinforced Concrete, Building Foundations, Cost model, Quantity model, Seismic Design

1. INTRODUCTION

Building foundation, as an interface structural component between the building and the supporting ground, perform the important function of transmitting the building loads including the wind and earthquake effects to the supporting soil strata without its shear failure or excessive settlements. At sites with potential for soil liquefaction under earthquake motions, appropriate measures interms of suitable selection and design of foundations and/or ground improvement techniques are considered based on detailed geotechnical investigations. The selection of suitable foundation systems for multistoreyed buildings are governed by several factors like; building loads, wind and earthquake effects, ground profile and water table conditions, chemically aggressive ground conditions, allowable bearing pressure of soils at different depths, provision of basement storeyes, proximity to adjoining buildings and other project specific requirements.

For medium rise multistoreyed developments with reinforced concrete framed superstructure, depending upon the building loads and allowable bearing pressure of soils, foundations with isolated footings under the individual columns or raft/mat foundations covering the entire footprint of the building are adopted. For buildings with below ground basement storeyes in high water table conditions, raft foundations are provided from the considerations of resisting buoyancy forces and easiness of providing a continuous external water proofing system. A more costlier and time consuming pile foundations are adopted when the building loads are required to be transmitted to a competent bearing stratum at deeper depths.

2. COST ASPECTS OF BUILDING FOUNDATION:

As the structural cost of the foundation system constitute one of the significant cost centers of the overall building cost, there is need to evolve suitable cost estimation approaches during early stages of design development and cost planning with considerations for seismic effects. Most of the preliminary cost estimation approaches are approximate and derived from the experiences of the constructed projects. The cost implications for incorporating various levels of seismic resistance for building foundations under different soil conditions is a much less understood aspect although some studies are available(1) on the cost premium for providing earthquake resistance for superstructure systems. From these considerations the study reported herein aims to provide an approach for the approximate cost prediction of building foundations and also to quantify the additional costs for providing seismic resistance under different levels of seismic forces over the non-seismic design conditions. Accordingly, this study presents the quantity and cost modeling of three types of foundation; isolated footings, raft and pile foundations for medium rise buildings under different soil conditions in different seismic zones of the Indian subcontinent.

3. BUILDINGS STUDIED:

3.1. Superstructure:

The proposed quantity and cost model are evolved for the foundations of typical medium rise reinforced concrete multistoreyed buildings with moment resisting frames. The structural grid consists of three bay frames (3m x 6m) spaced at 6.5m center to center, a commonly adopted economical structural system for office buildings in India Fig (1). In this study the building heights are varied from two to ten storeyes. While the solid slab panels are of 175mm thickness for all the case study buildings, the column sizes adopted are 400 x 400mm for two storeyed buildings and upto 650 x 650mm for ten storeyed buildings. The beam sizes are in the range of 300 x 500mm to 350 x 600mm. The 28 days characteristic compressive strength of concrete and yield strength of steel reinforcement adopted are 25N/sq.mm and 415 N/sq.mm respectively for all superstructure and foundation elements. For pile concrete a characteristic compressive strength of 35N/sq.mm is considered for durability.

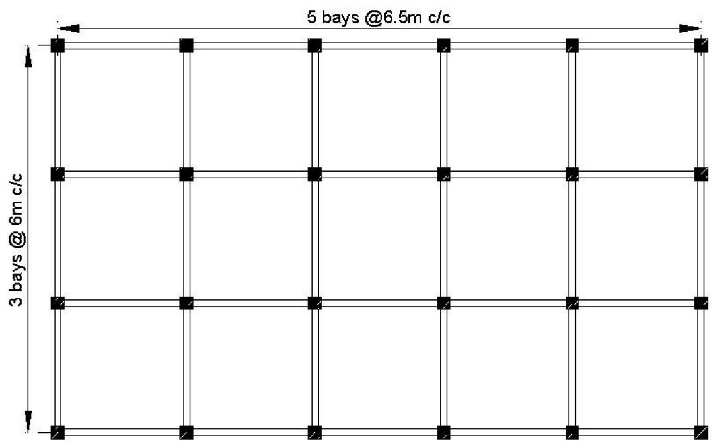


Fig.1. Structural configuration of a typical office building

3.2. Foundation:

The foundation types for the case study buildings are determined based on the building loads and allowable bearing pressure of soils as shown in Table (1). It is presumed that the foundations are laid on non-liquefiable soils under earthquake motions. The allowable bearing pressure of soils (ABP) considered for the shallow foundations are: 75, 100, 150 and 200 KN/sq.m at a depth of 1.50m below the ground level. Pile foundations with a system of pile groups, pile caps with grade beams are adopted for eight and ten storeyed buildings wherein shallow foundation are not considered feasible due to low allowable bearing pressure of soils at shallow depths. Use of below ground basement storeyes give advantage of increased net allowable bearing pressure of soils due to the removal of soil mass in the basement storeyes resulting more economical foundation systems. However, this aspect is not considered in the present study.

Table (1): Selection of Foundation system for the case study buildings

Buildings	Allowable bearing pressure of soils (KN/sq.m)			
	75	100	150	200
Two storeyed	Isolated footings	Isolated footings	Isolated footings	Isolated footings
Four storeyed	Isolated footings	Isolated footings	Isolated footings	Isolated footings
Six storeyed	Raft Foundation	Isolated footings	Isolated footings	Isolated footings
Eight storeyed	Pile Foundation	Raft Foundation	Isolated footings	Isolated footings
Ten storeyed	Pile Foundation	Pile Foundation	Raft Foundation	Isolated 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: 2002 [2]. 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.

Table (2): Intensities of seismic forces considered

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

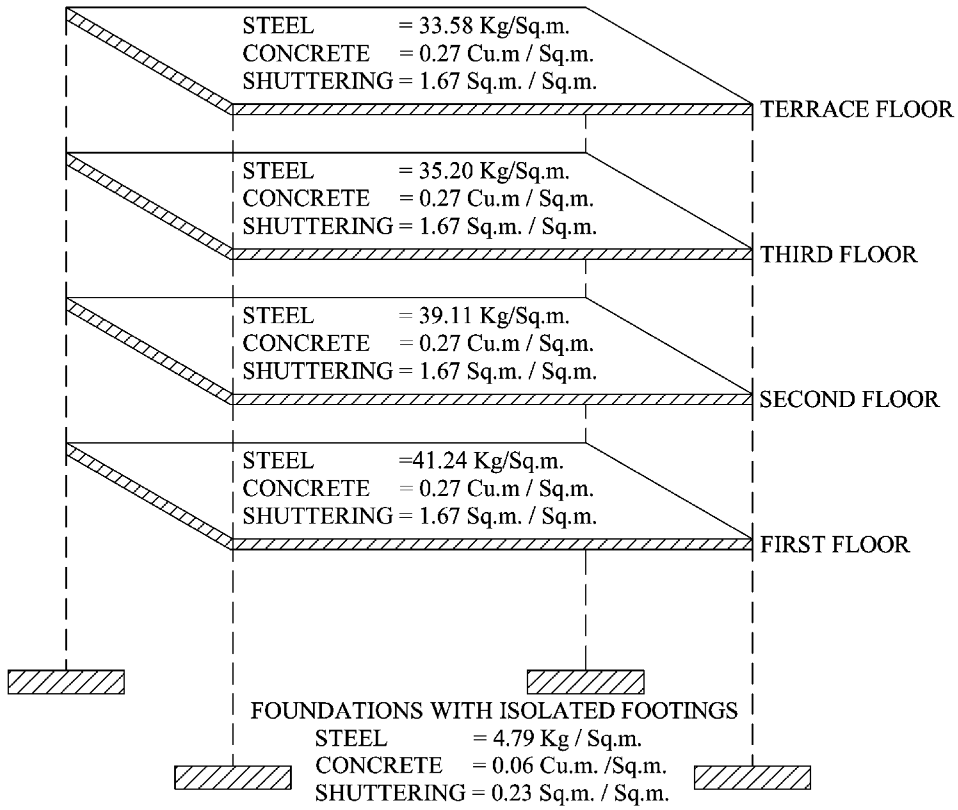
5. SEISMIC ANALYSIS AND DESIGN:

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 from the columns to foundations and with the knowledge of the allowable bearing pressure of soils, the type of foundations are decided and their structural designs and reinforced detailing were carried out in accordance with the Indian codes of practice [3]. 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 MODELING OF BUILDING FOUNDATIONS:

The quantity modeling 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. The non-structural elemental costs involved in the foundation such as earthwork items, temporary supports for excavation, dewatering are to be treated separately and do not form the part of structural cost model. For buildings with isolated footings, the foundation elements considered are footings, pedestals and grade beams connecting the pedestals. For raft foundations, slab of uniform thickness covering the entire footprint of the building with column pedestals are considered. For the pile foundations, piles, pile caps with pedestals and the tie beams connecting the pile caps are considered.

The proposed cost model for the three types of foundations considered takes into account three important parameters; number of storeys, allowable bearing pressure of soils and seismic zones and brings out the cost implications for designing the foundations for different levels of seismic forces. In the earlier study [1], the quantity and cost model for the superstructure system of the building is presented as the quantum and cost of structural quantities of the superstructure elements per unit floor area of the building.



Allowable Bearing Pressure = 150 KN / Sq.m.

Fig.2. Quantity model for a four storeyed building in seismic zone IV with Isolated Footings

***6.1. Quantity and Cost modeling of Foundations with Isolated Footings*:**

The structural quantities of isolated footing system with grade beams connecting the footings expressed in terms of quantities per sq.m of the floor area for different parameters 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 different seismic zones. The data presented also indicate the decrease in structural quantities and costs for improved allowable bearing pressure of soils.

i. The requirement of structural concrete per sq.m increases from 0.05 cu.m to 0.10 cu.m corresponding to the decrease in allowable bearing pressure of soil from 200 KN/sq.m to 75 KN/sq.m. Similarly the requirement of shuttering material varies from 0.18 sq.m to 0.46 sq.m per sq.m. However the shuttering cost is not significantly contributing to the structural cost.

ii. The variation in steel reinforcement is substantial and works out between 3 to 9 kg per sq.m of the floor area depending upon the variation in the three parameters. For 10 storeyed building, the percentage increase in the steel reinforcement is about 4, 11, 25 and 27% in seismic zones II, III, IV and V respectively. The corresponding values are 6, 10, 19, and 27% for 8 storeyed, 7, 11, 19 and 27% for 6 storeyed, 9, 17, 34 and 46% for 4 storeyed and 4, 13, 30 and 52% for 2 storeyed buildings.

iii. The cost premium for incorporating seismic resistance can be broadly taken as 3, 6, 15 and 20% for seismic zones II, III, IV and V respectively.

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

Storeys	ABP KN/Sq.m.	Non-seismic			Zone II			Zone III			Zone IV			Zone V		
		Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m
Two	75	0.09	5.60	0.46	0.09	6.07	0.46	0.09	6.41	0.46	0.09	7.79	0.46	0.09	8.47	0.46
	100	0.07	5.20	0.41	0.07	5.40	0.41	0.07	6.02	0.41	0.07	7.32	0.41	0.07	7.98	0.41
	150	0.06	4.80	0.34	0.06	5.01	0.34	0.06	5.43	0.34	0.06	6.2	0.34	0.06	7.32	0.34
	200	0.05	4.38	0.30	0.05	4.80	0.30	0.05	5.22	0.30	0.05	6.44	0.30	0.05	7.10	0.30
Four	75	0.10	4.74	0.36	0.10	5.28	0.36	0.10	5.55	0.36	0.10	6.18	0.36	0.10	6.71	0.37
	100	0.09	4.43	0.30	0.09	4.75	0.30	0.09	4.99	0.30	0.09	5.70	0.30	0.09	6.13	0.31
	150	0.06	3.56	0.23	0.06	3.87	0.23	0.06	4.15	0.23	0.06	4.79	0.23	0.06	5.19	0.24
	200	0.05	3.26	0.20	0.05	3.40	0.20	0.05	3.80	0.20	0.05	4.43	0.20	0.05	4.77	0.18
Six	100	0.01	4.23	0.27	0.10	4.49	0.27	0.10	4.91	0.27	0.11	5.07	0.28	0.11	5.39	0.29
	150	0.07	3.40	0.21	0.07	3.63	0.21	0.07	3.76	0.21	0.07	4.04	0.22	0.08	4.32	0.23
	200	0.05	2.89	0.18	0.05	3.14	0.18	0.05	3.28	0.18	0.06	3.71	0.18	0.06	3.97	0.18
Eight	150	0.07	3.40	0.20	0.07	3.63	0.20	0.08	3.76	0.20	0.08	4.04	0.21	0.09	4.32	0.21
	200	0.06	2.92	0.17	0.06	3.14	0.17	0.06	3.25	0.17	0.07	3.52	0.17	0.07	3.75	0.17
Ten	200	0.06	2.95	0.16	0.06	3.06	0.16	0.06	3.28	0.16	0.07	3.68	0.16	0.07	3.74	0.17

Table (4): Foundation with Isolated Footings: Structural cost and Cost premium for Seismic effects

Building	ABP KN/ Sq.m.	Structural cost in Rupees per sq.m of floor area					Percentage Increase in cost over Non-seismic case (NS)			
		N.S	Zone II	Zone III	Zone IV	Zone V	Zone II	Zone III	Zone IV	Zone V
2 storeyed	75	734	756	772	837	869	3.0	5.2	14.0	18.4
	100	617	627	656	656	748	1.5	6.2	16.1	21.1
	150	544	554	573	573	639	1.8	5.4	12.1	17.6
	200	473	493	513	513	601	4.2	8.3	20.4	27.0
4 storeyed	75	726	752	764	794	820	3.5	5.2	9.3	12.9
	100	658	673	684	718	739	2.3	4.0	9.0	12.3
	150	471	486	499	529	549	3.1	5.9	12.2	16.5
	200	408	414	433	463	476	1.6	6.2	13.5	16.8
6 storeyed	100	690	703	722	777	793	1.8	4.6	12.5	14.9
	150	484	495	524	538	598	2.2	8.2	11.2	23.6
	200	388	399	406	472	484	3.0	4.7	21.7	24.8
	150	524	534	554	564	632	2.0	5.6	7.7	20.7
8 storeyed	200	433	443	449	507	518	2.4	3.6	17.0	19.5
10 storeyed	200	433	439	449	513	517	1	3.6	18.5	19.4

6.2. Quantity and Cost modeling of Raft Foundations:

Raft foundations are considered for 6, 8 and 10 storeyed buildings for the sites with soil allowable pressures of 75 KN/sq.m, 100 KN/sq.m and 150 KN/sq.m respectively. The type of raft considered is of reinforced concrete slab of uniform thickness covering the entire foot print of the building with projection of 1m from the peripheral columns. The column bases are provided with pedestals at their junction with the raft to improve the punching shear resistance. A set of beams connecting the columns 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 thicknesses of the raft considered are 0.60m, 0.75m and 0.90m for the 6, 8 and 10 storeyed buildings. The raft analysis for various seismic zone conditions are carried out by modeling the raft with plate elements resting on the soil modeled as elastic springs using the modulus of subgrade reaction property of the soil. The design and reinforcement detailing are carried out and the structural quantities are determined for each of the seismic zones and the corresponding structural costs are worked out. The requirement of structural quantities and structural cost are presented in Table (5) and (6).

The concrete quantity is about 0.12cum/sq.m and the steel reinforcement varies in the range of 5.22 to 8.00 Kg/sq.m depending upon the number of storeyes and seismic zones. The cost premium for incorporating the seismic resistance could be broadly taken as 3 to 15% from Seismic Zone II to V. Taking into consideration the high cost ratio between steel and concrete, this cost premium could be lowered by optimal increase in raft thickness and decrease in quantum of steel reinforcement.

Table (5): Foundations with Raft Foundation: Structural quantities per sq.m of floor area

Storeys	ABP KN/Sq.m.	Non-seismic			Zone II			Zone III			Zone IV			Zone V		
		Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m	Concrete cu.m	steel kg	Shuttering sq.m
Six	75	0.12	5.34	0.02	0.12	5.62	0.02	0.12	5.90	0.02	0.12	6.54	0.02	0.12	7.65	0.02
Eight	100	0.11	5.22	0.02	0.11	5.72	0.02	0.11	6.30	0.02	0.11	6.70	0.02	0.11	7.80	0.02
Ten	150	0.12	5.87	0,02	0.12	6.10	0.02	0.12	6.40	0.02	0.12	7.10	0.02	0.12	8.00	0.02

Table (6): Foundation with Raft Foundations: Structural cost and Cost premium for Seismic effects

Building	ABP KN/sq.m	Structural cost in Rupees per sq.m of floor area					Percentage Increase in cost over Non-seismic case			
		N.S	Zone II	Zone III	Zone IV	Zone V	Zone II	Zone III	Zone IV	Zone V
6 storeyed	75	792	805	818	848	901	1.6	3.3	7.1	13.8
8 storeyed	100	750	773	801	819	871	3.1	6.8	9.2	16.1
10 storeyed	150	762	773	787	820	862	1.4	3.3	7.6	13.1

6.3. Quantity and Cost modeling of Foundations with Pile Foundations:

Pile foundations are considered for eight and ten storeyed buildings for which shallow foundations are not feasible. Individual columns are supported by pile caps interconnected by grade beams. Bored cast in-situ piles of 500mm diameter, 20m long placed at 1500mm center to center spacing having a safe load capacity of 750 KN as adopted in some of the building projects are considered. Under seismic conditions, the pile capacities are increased by 25% as per codal provisions. The number of piles in the group varies from 4 to 8 piles based on the support reactions at the column bases under governing load combinations of gravity and seismic loads. Pile foundation designs for each of the case study buildings under four seismic zone conditions and non-seismic conditions are carried out and structural quantities per sq.m of the floor area are worked out and presented in

Table (7) along with the corresponding structural costs based on the prevailing unit rates of these quantities for pile foundation works.

The concrete quantities per sq.m of floor area for the pile caps with grade beams and for the piles are about 0.06 cu.m and 0.10 cu.m respectively. The quantity of steel reinforcement for pile caps with grade beams per sq.m of floor area ranges from 3.5 to 4.7 kg/sq.m and for piles this variation is from 6.3kg to 8.2kg/sq.m. The cost premium for incorporating earthquake resistance in seismic zone IV and V is about 5 and 15% respectively.

Table (7): Pile Foundations: Structural quantities, cost and cost premium for Seismic effects

Building	Seismic Zone	Pile cap and Grade beam				Pile			Total cost Per sq.m	% increase in Cost
		Concrete cu.m/sq.m	Steel kg/sq.m	Shuttering sq.m/sq.m	Cost (Rs)	Concrete cu.m/sq.m	Steel kg/sq.m	Cost (Rs)		
8 storeyed	NS,II	0.055	3.52	0.1	429	0.10	6.28	1417	1846	-
	III	0.055	3.52	0.1	429	0.10	7.94	1495	1924	4
	IV	0.055	3.56	0.1	431	0.10	7.94	1495	1926	4
	V	0.058	4.53	0.1	477	0.11	8.97	1657	2134	16
10 storeyed	NS,II	0.055	4.25	0.09	461	0.10	6.15	1411	1872	-
	III	0.055	4.25	0.09	461	0.10	7.79	1488	1949	4
	IV	0.058	4.45	0.09	486	0.10	8.00	1498	1984	6
	V	0.058	4.69	0.09	497	0.11	8.20	1620	2117	13

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 (8) along with foundation types and soil parameter.

Table (8): Structural quantities of Foundations in actual buildings (per sq.m floor area)

Building	Seismic Zone	Foundation	Structural Quantities	
			Concrete Cu.m/Sq.m	Steel Kg/Sq.m
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. THE RESULTS OF THE STUDY:

The results of the study are summarized as under;

i) The study provides the requirement of structural quantities and corresponding foundation costs per unit floor area of the building for three types of building foundations incorporating the effect of variations in three parameters; number of storeyes, allowable bearing pressure of soils and seismic zones and the cost premium for seismic effects are quantified.

ii) For isolated footings, the concrete quantity variation is between 0.05 to 0.10 cu.m/sq.m due to variations in soil allowable bearing pressure of value of 250 to 75 KN/sq.m. The steel reinforcement varies from 3 to 9 Kg/Sq.m due to the variation in the three parameters. The cost premium for incorporating seismic resistance could be considered between 3 to 20% for low to high seismic zones.

iii) For raft foundations, the concrete quantity is about 0.12cum/sq.m and the requirement of steel reinforcement varies between 5.2 to 8 Kg/Sq.m due to variation in the three parameters. The cost premium for seismic resistance could be considered between 3 to 15% for low to high seismic zones.

iv) For pile foundations, the concrete quantity is about 0.16 cum/sq.m and the requirement of steel reinforcement varies between 10 to 13 kg/sq.m due to variation in seismic zones. The cost premium for seismic resistance is about 5 and 15% for moderate and high seismic zones.

v) Considering the high cost ratio between steel and concrete there is scope to lower the cost premium by increasing the concrete quantity and decreasing the reinforcement steel content in the design process.

vi) The quantities used in actually constructed buildings of different occupancy type, structural configuration and soil conditions suggests the reasonability of the present study and indicates the need for further investigations for other commonly adopted structural systems and configurations.

9. CONCLUSIONS:

The study has evolved the structural quantity and cost modeling of three types of foundation for medium rise reinforced concrete multistoreyed office buildings considering the variations related to number of storeys, allowable bearing pressure of soils and design seismic forces. The cost implications for incorporating the seismic resistances in low to high seismic zones of Indian subcontinent are quantified. The broad validation of the study is made with the presentation of the structural quantities of the actual buildings constructed in different seismic zones. Further studies are required to investigate and quantify the effects of different structural systems and configurations, occupancy types, soil conditions and foundation types and optimize the cost premium for seismic resistance. The study besides creating awareness on the cost implications for seismically designed foundations, presents an approach for the quantity and cost estimation of building foundations in construction management practice.

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