Codal Provisions for Foundation Design on Soils and Rocks: A Review

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Abstract. Usual design of building foundations are performed based on prescribed serviceability and strength criteria as laid down by various standard codes adopted by different countries. Generally, total settlement of a foundation is described under the serviceability criterion; whereas a strength criterion is described by bearing capacity of the soil or rock underlying the foundation. Both of these safeguard a foundation from its stability and structural integrity point of view against the acting design loads that may appear during its lifetime. The important most function of a foundation is to transfer super-structure load to the underlying strata which are composed of either soil or rock or both in layers. Engineering properties of both soils and rocks vary geo-spatially in small to large scale. In view of the wide spectrum of soil/rock characteristics, the analysis and design of foundations are provided by understanding of basic soil and rock mechanics principles. Although, a detailed analysis of site-specific solutions is a must for a vital and large-scale project as well as for a problematic site condition. Building codes present the most relevant guidance in design and construction of foundations. An attempt has, therefore, been made in the present study to revisit and compare foundation design methodology, by studying and investigating three popular design codes, namely Indian Standard Code (IS code), American Concrete Institute Code (ACI) and International Building Code (IBC) by the International Code Council (ICC). In this study, basic technical information on (i) 'general behaviour of soil and rock' i.e. nature of soil, rock types, stability and properties along with its behaviour under foundation, (ii) 'effect of groundwater' i.e. effect of underground water on foundation, (iii) 'foundation settlement' i.e. foundation failure modes, and (iv) 'preventive and strengthening measures' i.e. improvement of bearing capacity of strata through stabilizing methods, etc. have been covered in brief.

Keywords: Settlement, Bearing Capacity, Foundation Design, Standards and Codes; Comparative Study.

1 Introduction

Any building structure transmits its super-structure load through foundations which are constructed over soil or rock, together termed as sub-strata. Foundations are hence called the sub-structure buried beneath the natural ground level (NGL). Elementary design of a foundation is based on satisfactory bearing capacity and tolerable settlement of the sub-strata on which it rests [1]. Design load pressure in excess of the bearing capacity of the sub-strata causes ruptures and develops failure surfaces between the footing edges and ground surface. Diverse failure modes in the sub-strata have been observed and listed as (a) general shear failure: the load beyond ultimate bearing capacity develops, shear force within the soil underlying the footing causes its sudden settlement and bulging over the ground surface; (b) local shear failure: the settlement is accompanied by sudden jerks and little bulging over ground surface and further increase in load causes large settlement and heaving; and (c) punching shear failure: only vertical settlement of soil and footing occurs without any heaving on the ground surface [2, 3]. The design methodologies of sub-structure are thus formulated to suit the indigenous soil conditions for an efficient building design without foundation failure.

Some mechanical properties of soils and rocks are complex and difficult to determine precisely, probably because they are not a manufactured standard product like rolled steel or mix-designed concrete and the origin and process of rock and soil cycles are mainly governed by physical and chemical changes within their micro-structures. Further, the selection of site for construction of a building and its foundation is not entirely within the engineer's control and many times, a structure is to be built on an apparently weak soil site or highly weathered and fissured rocky topography. Hence, the stability and function of a building largely depend upon the behaviour of the soil or rock upon which it is built.

Characteristically, serviceability is typically a long-term trait for a building foundation related to time-dependent consolidation phenomenon of the bearing sub-strata, whereas, bearing capacity may be a short-term feature (e.g. an embankment construction on an undrained clay foundation) or a long-term feature where the maximum foundation load may appear at an unknown time. Usually, bearing capacity of shallow and deep or pile foundations is estimated using codal provisions developed after classical soil mechanics principles utilized by Terzaghi & Meyerhoff (Terzaghi, 1943 [4]; Meyerhof, 1951 [5]) and static formula by Tomlinson (1981) [6], respectively.

For the purpose of design of foundation, a number of codes are available in various countries around the world. As the soil and climatic conditions differ geo-spatially, the design parameters also alter accordingly, even if the principles of the design methodologies are essentially the same. However, a comparative study of the foundation codes have revealed some inconsistency in the principles considered for design methodologies which should be studied and modified, if and when necessary.

An attempt has, therefore, been made in the present study to revisit and compare foundation design methodology, by studying and investigating three popularly referred and used design codes, namely Indian Standard Codes (IS codes) [7-18], American Concrete Institute Codes (ACI) [19, 20] and International Building Codes (IBC) [21] by the International Code Council (ICC). In this study, basic information on nature of soil, rock types, stability and properties along with its behaviour under foundation, effect of groundwater on foundation, foundation failures, and improvement of bearing capacity of strata through soil stabilizing methods, etc. have been covered in brief.

2 Comparison of Codal Design Methodology

For the comparative study three international building codes, namely IS, ACI & UBC/IBC are considered. After studying and analyzing the different clauses of these codes, comparative discussions have been made along with highlighting some research gaps. These comparisons will facilitate the scope of improvement in building codes after further studies and validations.

There are several Indian Standards for foundation on soil and rocks like IS 1080 on "Code of Practice for Design and Construction of Shallow Foundations in Soils (Other Than Raft, Ring And Shell)" [7], IS 1904 on "Code of Practice for Design and Construction of Foundations in Soils: General Requirements" [8], IS 2911 (Part 1 to Part 4) "Design and Construction of Pile Foundations - Code of Practice" [9, 10, 11, 12], IS 6403 [13], IS 12070 on "Code of Practice for Design and Construction of Shallow Foundations on Rocks" [14], IS 13063 on "Code of Practice for Structural Safety of Buildings on Shallow Foundations on Rocks" [15], IS 14243 (Part 2) on "Guidelines for selection and development of site for building in hill areas" [16], IS 14593 on "Design and Construction of Bored Cast-in-situ Piles Founded on Rocks - Guidelines" [17] and IS 14804 on "Siting, design and selection of materials for residential buildings in hilly areas – Guidelines" [18]. Prevailing building codes on concrete constructions in the USA are provided in ACI: 318-14 [19], and ACI: 332R-84 [20]. The main regulations for foundations in the International Building Code [21] are located in Section 1808 (Foundations), Section 1809 (Shallow Foundations), and Section 1810 (Deep Foundations).

2.1 Depth of footing

According to all the considered codes in this paper, footing depth is the depth below the natural ground surface at which the required bearing capacity of soil/rock for load transmission is obtained. The clauses defining the depth of footing according to various codes have been listed below.

Indian Standard. All foundations shall extend to a depth of at least 0.5 m below NGL where the bearing strata is soil. This minimum depth is required to ensure the availability of safe bearing capacity and optimum frost depth [8] (sec. 7.1, 7.2). For foundation depth in rocks, Cl. 5.4 of [15] is referred to. It says that (i) in partially weathered, jointed and sheared rocks, foundation base is to be kept at least 0.5 m inside rock; whereas, (ii) for very low strength, rock, foundation material shall be treated to be as soil and depth is defined using IS 1904 [8] provisions; and (iii) for sound and massive rock, foundation line shall be above frost penetration limit.

ACI. Depth of footing above reinforcement should not to be less than 0.15 m even though firm bearing soil is found at a shallower depth. A practical minimum depth is taken as 0.25 m. However, the overall depth of pile foundation shall be selected such that the effective depth of bottom reinforcement is at least 0.3 m as per Cl. 13.3.1.2 and 13.4.2.1 of [19], and Cl. 8.3.2 [20].

IBC. According to IBC (sec. 1805.2 and sec.1805.2.1) [21], concrete footings and solid masonry foundations shall extend below the frost line. Foundation walls supporting wood shall extend at least 0.15 m above the finish grade adjacent to the wall at all points. However for masonry buildings, IBC suggests that, depth of footings shall extend to 0.3 m and should confirm to sufficient frost depth.

Discussion. After a preliminary overview, it is noted that the minimum foundation depth prescribed in IS codes is almost double than the other two referred standards. This may be due to heavy weight of solid masonry and concrete (the most common materials of construction used in India), as compared to various light weight IBS prevalent in other countries [22]. The IBC [21] prescribes regulations about commercial construction whereas IRC: The International Residential Code [23] prescribes regulation on residential construction along with home remodeling issues. Hence, the UBC/IBC [21] is a more generic code and prescribes range of values for the determination of the minimum depth of the foundation. IBC/UBC has also included considerations of frost depth in defining the minimum depth of foundation.

2.2 Cover to Footing Reinforcements

The main reason of providing the cover is to protect the reinforcement from the chemical agents present in the atmosphere. Because inappropriate cover depth results into the corrosion of constituent elements which ultimately reduce the life of the structure.

Indian Standard. Cl. 5.3.6 of [8] recommends a minimum cover of 50 mm for footings. But the actual cover may be even more depending on the presence of harmful chemicals, water table etc. For locations with considerable salt and sulphate content in water, Cl. 26.4.2.2 of IS 456: 2000 [24] suggests that dense M-20 concrete along with pozzolana could be used. A thick layer of bitumen can be laid before laying foundation concrete, to prevent infiltration of water from sulphate bearing soil.

ACI. American building Code [19] specifies the cover depth for different regions (Table 1).

IBC. There should be a minimum of 3 inches (7.62 cm) concrete between reinforcement and the other main structural member in which the concrete is deposited against the ground and 2 inches (5.08 cm) for concrete surfaces which are just in contact with natural ground level. IBC also suggests a concrete cover of 3.2 cm for prestressed square piles of 12 inches (30.5 cm) or smaller size and 3.8 cm for larger piles. For foundations exposed to seawater, the minimum 6.4 cm of protective concrete cover is prescribed in Sec. 1809.2.3.5 of [21].

The following Table 1 gives a summary of concrete cover specification by ACI code [19].

Table 1. Summary of concrete cover specification by ACI code [19].

Concrete exposure	Member	Specified cover (mm)
Permanent ground contact	All	75
Exposed to weather or in contact with ground	All	40 to 50
Not exposed to weather or in contact with ground	Slab joists	40
	Walls	20
	Beams, columns, pedestals, and tension ties	40

Discussion. ACI specifies the cover thickness depending upon the type of reinforcement. However, the IS and IBC codes specify concrete cover to foundation as per the climatic conditions irrespective of the provided diameter of the foundation slab reinforcements.

2.3 Longitudinal reinforcement and Dowel length

The forces and moments developed at column face must be conveyed to footing through the pedestal. The compressive force is delivered to the concrete while the tensile force is taken by the reinforcement steel. However, for balancing large permissible bearing stresses dowel bars or column extensions should be provided.

Indian Standard. As prescribed in IS, these extending bars should be at least 0.5 percent of the cross-sectional area of the supported column or pedestal. Minimum of four bars shall be provided whose diameter should not exceed the diameter of column bars by 3 mm as per Cl. 34.4 of [24].

ACI. For columns, minimum dowel reinforcement is given as, As (min.) = 0.005 Ag, where Ag is column gross cross-sectional area. Required dowel reinforcement is given by:

As (req) = (Pu – Φ * Pn) / (Φ * fy), where the value of strength reduction factor (Φ) is 0.65, as per Cl. 15.8.2.1 of [19].

IBC. According to IBC [21], the total sectional area of dowels shall not be less than the sectional area of the longitudinal reinforcement of the member and in no case less than four dowels should be used. Also, the diameter of the dowels shall not exceed the diameter of the column bars by more than 1/8 inch (nearly 3 mm) as per Sec. 2623 (h) of UBC [25].

Discussion. As per IS and ACI codes, the minimum sectional area of dowels should be 0.5% of the sectional area of the column or pedestal whereas, in UBC/IBC the corresponding minimum area is simply taken as equal to column reinforcement. This lead to contradiction and diverse values, because different codes have different methods for defining the minimum nominal reinforcement.

2.4 Allowable lateral soil or rock pressure and bearing capacity

The bearing capacity or allowable lateral soil pressure of soil is the gross pressure that the footing can withstand such that, the soil doesn't fails in shear and settlement occur within the safe limits [3, 15].

Indian Standard. As per Sec 5.2.2.1 of [13], the equation for calculating of ultimate bearing capacity is:

$$Q_{nu} = c*(N_c\, i_c\, S_c\, d_c) + q*(N_q-1)*(i_q\, S_q\, d_q) + 0.5B\gamma * N_\gamma * (i_\gamma\, S_\gamma\, d_\gamma) * W'$$

Where, $N_\gamma = 2(Nq+1) \tan\Phi$

$N_c = (Nq-1) \cot\Phi$

and, $N_q = e\wedge\pi*\tan\Phi*\tan^2(45^0+\Phi/2)$

Here, S, d and i are empirical correlation factors for shape, depth and inclination of loading respectively.

If depth of water below ground > (D_f) then, reduction factor, W' = 1

If water table at depth = (D_f), then, W' = 0.

As per, IS 12070 [14], Cl. 4 gives calculation of safe bearing pressure (SBP) on rock based on rock mass material types (massive crystalline bedrock, having SBP 1000 t/m^2 to Soft or broken bedrock, having SBP 40 t/m^2). Although, universally applicable SBP values based on rock mass classification cannot be given but, according to Cl. 5 of [14], Rock Mass Rating (RMR) values (100 to 0) could be used to determine SBP values (600-448 t/m^2 for RMR = 100 to 81, to 55-45-40 t/m^2 for RMR = 20 to 0). For good quality rock with wide joint spacing i.e. 1 m to ≥ 3 m, Cl. 6.1 gives an empirical equation to determine SBP based on average UCS of rock cores. Alternatively, Cl. 7 of [14] suggests an empirical equation based on pressure-meter tests to determine SBP for low strength fragmented or weathered rock masses with closely spaced (5 to 30 cm) discontinuities. In common practice, such cases are considered as granular mass and foundation design is based on conventional soil mechanics. Again, Cl. 9 of [14] outlines a different method to calculate the SBP based on plate load tests performed at field on poor rocks suspected to have bearing capacity less than 100 t/m^2.

Although, SBP values can be calculated based on above methods, but settlement criterion often plays the pivotal role in limiting the SBP value which is finally taken for foundation design. Total settlement shall not be more than permissible settlement as prescribed in Cl. 5.2.2 of [15], whereas, differential settlement and tilt of the building shall be not more than the recommended values specified in Cl. 5.2.3 of [15].

ACI. The theoretical bearing capacity of soil (X_1) can be calculated as, $X_1 = (q_{ult} * m_1 - \gamma * D_f)$, where, m_1 = model error for the bearing capacity. According to Meyerhof (1995) [5], the model error m_1 can be represented by a random variable with a bias factor of 1.0 and a coefficient of variation of 0.25.

IBC. Allowable foundation pressure and lateral bearing pressure of soil or rock as per IBC [21] is given in Table 2 below.

Table 2. Allowable foundation pressure and lateral bearing pressure of soil/rock as per IBC [21].

Class of materials	Allowable foundation pressure (kN/m^2)	Lateral bearing pressure of soil (kN/m^2)
Bed rock	575	575
Sedimentary rock	190	19
Sandy gravel	145	9.5
Sand	95	8
Clay	70	5

Discussion. Allowable bearing capacity in different building codes are different which can be used for proportioning footings. On the basis of the building's performance, a presumptive bearing capacity value is assumed. But these values are used only for preliminary design or for less important structures [26]. It is recommended by IS 1904 [8] that the safe bearing capacity should be estimated only after analyzing soil test data. If water table is present near the footing on non-cohesive soil, then these values should be further reduced to 50%.

2.5 Foundations adjacent to slopes

Cl. 10.2 of IS 1904 [8] stipulates the different requirements for construction of building foundations on a sloping terrain. It says that any construction on a suspected unstable landslip area should be avoided. Spread footing on sloping sites should be prepared resting on horizontal bearing strata by making a stepped ground profile by cut and fill method. At all level changes, the footings should be lapped at the steps for a minimum distance of foundation thickness or twice the height of step, whichever is the maximum (Cl. 10.2.4 of [8]). On valley side, clearance on valley side i.e. the minimum edge distance of the footing from slope's crest should be more than 1.5 m and should rest on a firm soil or rock as per Cl. 6.1 of IS 14243 Part 2 [16].

3 Strengthening Measures for Foundations

There are some guidelines provided by the IS codes to strengthen the foundation of buildings to make it stable under the prevailing design loads. These guidelines may be summarized as below:

- For water covered bearing strata, suitable drainage arrangement shall be provided (Cl. 6.2.5 of [15]). For prevention of water entry into foundation, a minimum of 0.75 m wide apron should be provided all around the building (Cl. 6.3 of [16]).
- For wide joints, cracks, areas of disintegrated rock, the foundation should grouted with 1:1 cement sand mortar up to maximum frost depth [15].
- If at the time of actual excavation, major solution cavities have been found which have rendered the ground surface uneven, the depth of foundation should be taken to a level such that 80% rock area is available. It must be ensured that the raft does not over hang at any corner (Cl. 10.1 of [15]).
- Due attention should be paid to problems of foundation on heterogeneous rocks, particularly foundations on rock slopes and necessary remedial measures should be taken (10.5 of [15]).
- Foundations should be checked for total and differential settlements to trace any distress in the foundation after construction of the super-structure [27].
- The foundation should be well beyond the influence shear zone created due to cuttings or excavations or due to proximity of the foundation to a sloping ground (Cl. 10.2.5 of [8]).
- If the probable slip surface passes through a support structure like a retaining wall, then it should be made strong enough to resist any unbalanced thrust coming due to slope movement.
- The minimum horizontal spacing between an existing footing and a new one shall be equal to the width of the wider one (Cl. 14 of [8]).

4 Conclusion

The present comparative study of foundation design methodology was taken up by studying and investigating several design codes that prescribes the standards for the efficient foundation design. Later in this paper, contrasting discussions of clauses along with some propositions are thus been delivered for further detailed analysis for codal improvement. However the study here has been limited to only three code of practice of foundation design. It has been found that in some sections, a common basic assessment criteria has not been followed, and hence should be considered for future ongoing studies.

Though the codes listed above provide every necessary details of foundation design, but there is a need to update the depth consideration in the Indian Standards in accordance with the various climatic classifications. Footing located at insufficient depth is subjected to frost damage due to formation of ice lenses and consequent frost heave. During summer, thawing occurs and melted water is entrapped. As the soil water freezes and melts, the footing is lifted during cold weather and it settles during warm weather due to an increase in water content. To prevent frost damage, the footing should be placed below the frost depth, which may be 1 m or more in cold climate [1, 26]. India being considered a tropical country, the frost depth has not been taken into consideration while calculating minimum footing depth. However, several regions in India record snowfall in winter and hence this criteria should be considered in the codal methodology. Also in Annexure-V of CPWD handbook of plinth area rates, the depth dependency is based upon the soil bearing capacity alone [28]. Between the different building codes of the United States, it is difficult to determine which frost penetration charts should be followed. However, in warm states for concrete or block wall foundations, frost depth could extend to 45 cm whereas in regions like Canada and Alaska, the required depth can even extend to 150 cm. Similar to these charts, a frost depth map is also needed suiting to the geophysical conditions of the Indian terrain.

On the other side, the IBC and ACI codes give more descriptive details of concrete cover to reinforcements for foundations which should be followed in Indian standards. According to ACI, even if the bearing strength of concrete is not exceeded, reinforcement must be provided at column interface. This type of specification is not provided in other two codes. Also ACI provides the upper limiting value of dowel reinforcement i.e. no. 36 (35.81 mm in dia.), while IS and UBC agree on the minimum diameter of dowel should not extend the diameter of reinforcement by 3 mm. Dowels should extend in supported member at least the greater of the development length of the longitudinal bar in compression which is entirely different due to different methods of design. Apart from this, there is requirement of a standard formula in IS code for calculation of dowel reinforcement.

The comparison drawn between different codes for the presumptive safe bearing pressures of foundations on different soils and rocks show much variance in the values of SBP, even for the same type of soil. Though the soil characteristic of different regions are different but this much deviation should be taken into consideration and needed to be checked again.

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