Raft foundations design charts: development and applications

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Abstract. Presented in this paper design charts for estimating effective depth of raft slabs on elastic foundation are developed in compliance with punching shear design procedures provided by Russian Design Code (SP) for reinforced concrete. Codes’ formulas are generalized to include only independent parameters omitting unnecessary calculations of critical section geometry. Proposed approach considers raft slab effective depth as a function of cross section sizes of vertical members (walls, columns) only. In the conclusion reasonable range of raft slab thickness to column sizes ratios have been established for numerical tests and experiments included in fundamental studies of moderately thick plates and raft slabs resting on elastic foundations.

Keywords: Raft foundations, punching shear capacity of reinforced concrete slabs, moderately thick plates, plates on elastic foundations, design charts.

1. Introduction

Structural frames of tall buildings consist of walls and columns which transfer high gravity and lateral loads to the soil bed through the foundations. For medium-stiff and stiff soils stratum underlying the land plot of the project, it is raft slab which becomes preferable option for building foundations.

The most general principles of raft engineering are outlined by ACI Committee 336 [1] and include three major steps as follow: punching shear design, bending analysis and settlements check, the results of which depend upon large variety of the design parameters discussed in [2-4].

It is common practice to carry out raft foundation analysis with FEM-software utilizing classical thin plates FE for modeling raft slab. However this approach does not produce accurate results in the close proximity of columns and walls supports. This problem could only be solved with moderately thick plates (Midlin-Reissner plate) theory which has been widely employed to develop a number of analytical and numerical methods suitable for raft foundation analysis [5-16].

Ratio of raft slab depth to the dimensions of column footprint area $h_0/h_c$ is a key parameter affecting the accuracy of the results produced by moderately thick plates theory. Therefore it is important to establish a reasonable range of $h_0/h_c$ values to be used for verification tests and experiments. Such range can be obtained by simplified engineering method similar to those described in [17-19]. It is based on the assumption that effective depth of raft slab $h_0$ is controlled by punching shear force caused by axial column load $F$ distributed over column footprint area $h_c \times h_c$ which sizes are resulted from the columns design. Therefore, two main parameters of punching shear calculation procedure – perimeter of punching shear critical section $u$ and design load $F$ transferred by column to the raft slab – are not independent. Hence, the purpose of this work is to work out simplified procedure for raft slabs depth calculations which would allow to establish practical range of $h_0/h_c$ ratios to be used in the fundamental studies of moderately thick plates on elastic foundation.

2. Methods of research

Brittle mode of failure caused by punching shear is always a concern. Therefore it is common practice to take most conservative assumptions to punching shear design such as:
– punching shear capacity of a raft slab equals to full axial capacity of a column;  
– punching shear capacity of a raft slab is provided by concrete only, while vertical reinforcement and soil pressure are neglected.

For writing punching shear expressions reference is made to figure 1a (drawing 16 [21]). Vertical member of the structural framing is represented by square column with cross-section sizes $h_i \times h_i$, which is built of normal weight concrete with compressive strength $R_{col}^{ult}$ and steel reinforcing bars with total area $A_{sc}$ and design strength $R_s$. Column has reinforcement ratio $\mu = A_{sc}/h_i^2$. Raft slab is built of normal weight concrete with $R_{bt}^{ult}$ tension strength. It’s effective depth equals to $h_0$.

![Figure 1](image1.png)

**Figure 1.** Punching shear design schemes a) raft slab on elastic foundation; b) pile cap

According to [21] design load $F$ applied to a raft slab over $h_i \times h_i$ column footprint area shall not exceed punching shear capacity $F_{b,ult}$ of raft slab critical section, located at a distance $d/2$ from the face of the column, i.e. $F \leq F_{b,ult}$. $F_{b,ult}$ is defined by expression (6.8.88 [20]):

$$F_{b,ult} = A_b \left( \gamma_{bt} R_{bt}^{ult} \right),$$

where $\gamma_{bt} = 0.9$ is concrete strength reduction factor for long-term static loads (i.6.1.12a [20]).

$A_b = u \cdot h_0$ is an area of punching shear critical section and it is calculated as follows:

$$A_b = u \cdot h_0 = 4(h_i + h_0),$$

where $u = 4(h_i + h_0)$ is a perimeter of punching shear critical section.

Substituting (2) in (1) we obtain:

$$F_{b,ult} = 4(h_i^2 + h_i h_0)\left(\gamma_{bt} R_{bt}^{ult}\right).$$

At the same time, design load $F$ may not exceed axial capacity of a column $N_{ult}$, i.e. $F \leq N_{ult}$,

where

$$N_{ult} = (h_i^2 - A_{sc})\left(\gamma_{bt} R_{bt}^{ult}\right) + A_{sc} R_s = h_i^2 \left(\gamma_{bt} R_{bt}^{ult}\right) + A_{sc} \left(R_s - \gamma_{bt} R_{bt}^{ult}\right)$$

$$= h_i^2 + A_{sc} \left(\gamma_{bt} R_{bt}^{ult}\right) - 1 \left(\gamma_{bt} R_{bt}^{ult}\right)^{-1} \left(\gamma_{bt} R_{bt}^{ult}\right) = h_i^2 \left[1 + \mu \left(R_s \left(\gamma_{bt} R_{bt}^{ult}\right)^{-1} - 1\right)\right]$$

where $\gamma_{bt} = 0.85$ is concrete strength reduction factor for vertical elements higher than 1.5 m (i.6.1.12c [20]).

![Figure 2](image2.png)

**Figure 2.** Columns capacity diagrams $F_i = N_{ult} \left(\frac{h_i^2 R_{bt}^{ult} \gamma_{bt} \gamma_{bt}}{R_s}ight)$
It is reasonable to conclude that punching shear capacity of raft slab critical section $F_{b,ult}$ shall be bigger than column axial capacity $N_{ult}$, i.e. $F_{b,ult} \geq N_{ult}$. Combining expressions (3) and (4), we get:

$$4\left(h_0^2 + h_0h_1\right)\left(\gamma_{b1}R_{bt}^{op}\right) \geq h_1^2F_1\left(\gamma_{b1}\gamma_{bt}R_{bt}^{col}\right), \quad (5)$$

where

$$F_1 = \left[1 + \mu\left(R_s/\left(\gamma_{b1}\gamma_{bt}R_{bt}^{col}\right) - 1\right)\right] \quad (6)$$

Divided by $4h_1^2\left(\gamma_{b1}R_{bt}^{op}\right)$ expression (5) yields to quadratic equation for unknown variable $(h_0/h_1)$:

$$(h_0/h_1)^2 + (h_0/h_1) - (F_1/4)(\gamma_{bt}R_{bt}^{col}/R_{bt}^{ult}) \geq 0. \quad (7)$$

Discriminant of equation (7) equals to $\sqrt{F_1\left(\gamma_{bt}R_{bt}^{col}/R_{bt}^{ult}\right) + 1}$, and one positive root is defined as:

$$h_0/h_1 \geq \left(\sqrt{F_1\left(\gamma_{bt}R_{bt}^{col}/R_{bt}^{ult}\right) + 1} - 1\right)/2. \quad (8)$$

Graphs shown on figure 2 represent unitless parameter $F_1$ that is a ratio of axial capacity of reinforced concrete column $N_{ult}$ with reinforcement ratio $\mu$ to axial capacity of concrete column without reinforcement $F_1 = N_{ult} / \left(h_1^2R_{bt}^{col}\gamma_{b1}\gamma_{bt}\right)$. Therefore, section size $h_1$ of a square column subjected to an axial load $F$ can be calculated as follows:

$$h_1 = \sqrt{F_1\left(\gamma_{bt}R_{bt}^{col}\gamma_{b1}\gamma_{bt}\right)} \quad (9)$$

3. Results and Discussion

3.1 Raft slabs effective depth design charts

To facilitate raft slab effective depth calculations even further it seemed to be reasonable to provide design charts for reinforced concrete columns and raft slabs built of specific materials. Calculated for $R_{sc} = 435 \text{ MPa}$ those charts and tables are presented below on the figure 3a – 3f of this paper. Columns reinforcement ratio varies from 0.5% to 5%.

Particular range of columns concrete grades was considered for each concrete grade of raft slabs. From the practical experience it was assumed that raft slabs are built with normal weight concrete of B25 – B50 grades. Concrete grade selected for a raft slab may not be higher than concrete grade of any vertical member including columns and walls. On the other hand, column concrete grade usually does not exceed raft concrete grade by more than twice. For example, B25 – B50 concrete grades is found to be reasonable range for raft slab built of B25 concrete, and so on.

3.2 Simplified design procedure of raft slab thickness calculations

Formula (8) derived in the previous section allows to calculate directly raft slab effective depth $h_0$ as a function of square column section size $h_1$ and mechanical properties of raft slab and column materials:

- compression strength of reinforced concrete column $R_{bt}^{col}$,
- compression strength of column reinforcement $R_{sc}$ and it's reinforcement ratio $\mu$,
- tension strength of concrete raft slab $R_{bt}^{ult}$.

When conservatively sizing raft thickness for full axial capacity of a column $N_{ult}$ it is not necessary to know actual column load $F$ applied to the raft slab. All calculations related to the geometry of punching shear critical section are also omitted since it’s already accounted by formula (8). As soon as all of the listed above parameters $-R_{bt}^{ult}$, $R_{bt}^{col}$, $R_{sc}$, $\mu$, $h_1$ – are known from the building superstructure design stage, raft slab thickness can be calculated with one single formula (8) without any iterations.
Figure 3a. Columns (B25-B50) – raft slab (B25) design chart

Figure 3b. Columns (B30-B60) – raft slab (B30) design chart

Figure 3c. Columns (B35-B70) – raft slab (B35) design chart

Figure 3d. Columns (B40-B80) – raft slab (B40) design chart
3.3 Analysis of design assumptions and design optimization

Design charts presented on the figure 3a – 3f are calculated for square columns with most conservative assumptions described above. Therefore, $h_c/h_0$ values shown in Appendix A represent extreme maximums which can be further optimized on the latest design stages if needed. Appendix A is also applicable for rectangular columns since its perimeter would always be bigger than perimeter of square columns with the same area. Formula (8) can be easily modified to consider actual shape of column cross section with given area $A_c$ and perimeter $p_c$, and to replace column axial capacity $N_{ult}$ with column load $F$ reduced by value of shear strength provided by raft slab transverse reinforcement and soil pressure:

$$h_0/h_c \geq \left( \frac{F_{red}/(A_c R_{ult} \gamma_k)}{1 + 1 - \mu} \right)^2, \quad h_c = p_c / 4$$

(10)

3.4 Comparison with raft slabs design charts developed previously

Quite complex approach have been utilized by authors of [19] for developing raft slab thickness design charts based on specific building geometry, loadings and geotechnical conditions. Therefore practical application of those charts is much more limited than simple design diagrams presented herein. However, within the most common domain of generalized engineering parameters both approaches show good correlation of the results quantitatively and qualitatively.

3.5 Example problem

Using design charts presented on figures 2 and 3a estimate size $h_c$ of a square column subjected to an axial load $F = 1500\text{t}$ and calculate effective depth $h_0$ of raft slab assuming column reinforcement ratio $\mu = 2\%$, column concrete grade B40 and raft concrete grade B25.
1. For column concrete grade B40 and $\mu = 2\%$ on figure 2 find $F_i = 1.5$.

2. Calculate $h_c = \sqrt{\frac{F}{F_i R_{col}^m \gamma_{b1} \gamma_{b2} \gamma_{b3}} = \sqrt{\frac{1500}{(1.5 \cdot 2200 t/m^2 \cdot 0.9 \cdot 0.85)} = 0.771m \approx 0.78m}$

3. Find $h_0/h_c = 2.1$ - design chart on figure 3a

4. Calculate effective depth of raft slab: $h_0 = 2.1 \cdot h_c = 2.1 \cdot 0.78m = 1.638m \approx 1.64m$

Design requirement $F \leq F_{ult}$ can be checked by substituting $h_c$ and $h_0$ calculated above into (3):

$$F = 1500t < F_{ult} = 4(h_0^3 + h_0^2 h_c) (\gamma_{b1} R_{ult}^m) = 4((1.64m^3) + 1.64m \cdot 0.78m) (0.9 \cdot 105t/m^2) = 1500.2t$$

4. Conclusion

In this work effective depth of the raft slabs is considered as a function of an axial capacity of the column. This approach is quite reasonable since such important design parameters as building geometry (number of the floors, column spacing etc) and specific loading conditions are already accounted in the column design itself. Then it allowed to develop raft slabs design charts applicable to any buildings or structures subjected to any loading conditions prescribed by design codes [20-23].

As it was demonstrated in the example problem solved above in section 3.5, proposed design method utilizing raft slabs design charts in conjunction with column capacity diagrams (figure 2) allows calculating column sizes and raft slab effective depth in 4 simple steps which greatly facilitate the design workflow of structural engineering practitioners. Since the design charts are strictly based on the structural requirements and formulas provided by SP design codes [20, 21], they can be used as a part of regular design practice followed by submitting the results to authorized institutions as a part of construction permit process.

It can also be noted that presented design charts can be easily adjusted to include concrete cylinder strength $f_c$ and safety factors $\phi_i$ used by Eurocode 2 [23] and ACI 318 [22] as design input data instead of concrete cubic strength of concrete $R_p/R_{ult}$ and safety factors $\gamma_{b1}$, $\gamma_{b2}$, $\gamma_{b3}$ utilized by Russian SP [20, 21].

Finally, analysis of the data presented on developed raft slab design charts leads to the conclusion especially important for researchers conducting fundamental study of moderately thick plates on elastic foundations. It can be observed that calculated practical values of raft slabs effective depth to column size ratio $h_0/h_c$ vary from 1.4 to 2.9. These values define the most practical range for numerical tests and experiments carried out by researchers to verify newly proposed design methods, fundamental approaches and solutions.

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