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Comparison of Raft and Folded Plate Foundations

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Abstract

The design of raft depends on several factors like the stiffness of superstructure and foundation, bearing capacity or modulus of subgrade reaction of the soil, column spacing, projection of raft beyond the outer lines of boundary columns and the material strengths used in construction. For a given arrangement of superstructure, soil strength is the most important factor affecting the design and cost of construction of a raft. Folding of a raft or folded plate foundations can be used effectively to reduce the material consumption in a raft construction. A raft folded in straight lines is easy to construct and it increases the stiffness of the foundation, which in turn reduces the total and differential settlements of the structure as a whole. The present study compares the performance of raft and folded plate foundation. The advantages of folding the raft on the structural design of foundation and superstructure are highlighted. The initial designs were prepared using Winkler method and the impact of varying the coefficient of subgrade reaction on the design of raft and folded plate foundations were compared. Then continuum method was used for representing soil and its properties were varied in line with the variation in coefficient of subgrade reaction. The impact of this modeling and variation in soil properties on the foundation and super structure design were also compared. In addition the effect of increase in projections to the raft beyond the outer lines of boundary columns are also presented.

Keywords: Raft foundation, folded plate foundation, Winkler model, coefficient of subgrade reaction, continuum analysis, Stress-Strain modulus, Mohr-Coulomb model.

1.0 Introduction

1.1 Overview

Raft foundations are provided when the contribution of soil bearing from most of the area below the structure is required for load carrying. Rafts are also recommended in situations where soil is not that weak to need pile foundations but isolated footings cannot be recommended due to the possible higher differential settlements. Sometimes rafts are provided to act as a solid water proofing membrane covering the entire foundation area. The design of a raft depends on the stiffness of superstructure (SS), column spacing, projection of raft beyond the outer lines of boundary columns (PR), raft thickness, soil stiffness, strength of concrete and yield strength of steel. Among the various parameters listed above, strength of concrete is decided considering the site specific needs and limitations in achieving the maximum strength of concrete. Column spacing is decided by the architectural needs. The SS and substructure are provided with sufficient sizes to give a safe and economic structure. The soil strength, which is bearing capacity in conventional method of design of a raft, is one variable in which the designer has very limited control. In conventional analysis, uniform bearing pressure is assumed below the raft which may be the case for soil in a fluid state. In the case of analysis carried out using commercially available software, the soil media may be represented by a system of identical but mutually independent, closely spaced, discrete and linearly elastic springs and this method is based on Winkler's hypothesis (1867). The elastic constant of assumed springs is referred to as the coefficient of subgrade reaction, k_s and is defined as

$$k_s = \frac{q}{\delta}$$

Where q is the load per unit area (or contact pressure) and δ is the settlement under the loaded area.

In actual case, base pressure may vary from point to point depending on the load, rigidity of SS and type of soil and Winkler method is capable of representing the variation better than bearing capacity. Once the raft settles, the contact pressure is re-distributed depending upon the stiffness of foundation and SS, which in turn changes settlement. Settlement of the raft is also affected by other factors such as the increase in Stress-Strain Modulus- E with depth of soil below raft and the consolidation of soil. As k_s is evaluated from pressure and settlement, it is a variable depending on the several factors listed above and hence its computation is very difficult. The k_s values are obtained using Plate load test, Triaxial Test, Consolidation Test, CBR test or Empirical and theoretical relations (Bowles, 1997). Plate load tests are conducted using small plates of size varying from 30 cm to 76 cm. The stress increase in the soil due to loading the plate is felt over a small area under it. The stress increase under a foundation or raft influences a large area and hence Terzhagi (1955) suggested an expression for correction for size effect of foundation for the obtained values from plate load test. However even after the corrections, the actual settlements were underestimated especially when soil properties vary with depth (D'Appolonia 1968). Bowles (1997) suggested the ranges for k_s for sandy soil as given in Table 1. The value of k_s may be determined by semi-empirical methods like that proposed by Vesic (1961). Scott (1981) proposed empirical expression connecting k_s with standard penetration resistance (N) for sandy soils.

Table 1: Values of k_s for sandy soils

Type of Soil	k_s in kN/m^2/m
Loose Sand	4800-16000
Medium Dense Sand	9600-80000
Dense Sand	64000-128000
Clayey Medium Dense Sand	32000-80000

Table 2 : Stress –Strain Modulus (Bowles, 1997)

Type of soil	E in kN/m^2
Sand-Silty	5000 to 20000
Sand-Loose	10000 to 25000
Sand Dense	50000 to 81000

The simplifying assumptions on which Winkler model is based causes some errors (Terzhagi, 1955).The springs are neither elastic nor independent. The settlement due to the applied load at one point of the raft is felt in the adjacent areas and hence a uniformly loaded raft may exhibit a dish shaped settlement, unlike the uniform settlement predicted by Winkler (Coduto, 2001). Hence efforts were made to couple the springs so that the effect of vertical load can be transmitted in the lateral direction (Horvath, 2010, 2011). Continuum methods are another improvement over Winkler method in which soil media is represented by 3D finite elements. However continuum analysis is time consuming and assigning the representative soil properties to the model is very difficult. In contrast, the Winkler foundation is very simple and large numbers of software are available based on this method, capable of analysis and design of rafts meeting different country specific codes of practices. The difficulty in obtaining a representative k_s led ACI committee 336 (1988) to recommend that the raft designs be carried out varying the value of k_s over a range of one half to 5 or 10 times the furnished value. The furnished value in a soil report is hereafter called the designated value of k_s. The impact of varying k_s in the design of raft foundations was studied and no significant increase in the reinforcement was required when rafts were designed for a wide range k_s values (Thulaseedharan and Narayanan, 2013). The maximum bottom and top bending moments in a raft generally reduces as k_s

increases. The comparisons of Winkler and Continuum methods showed that results are nearly similar and k_s based methods are sufficient for design purposes of flat rafts. A projection given beyond the outer lines of boundary columns reduces the top moments in a raft. It will also increase the area resisting punching shear for outer columns. The effect of top moments in a raft is felt over a large area and requires reinforcement to be placed accordingly. Generally the design bending moments at bottom at the face of columns are much more than the top moments. However it reduces to such values which will be taken care by the minimum reinforcement provided, within a small area surrounding the columns. Hence the rest of the area of raft in the bottom other than support area is given only nominal reinforcement satisfying crack width limitations. Hassan (2011) studied the variation of raft deflection with k_s at various locations in a raft and the influence of column spacing and raft thickness on settlement of raft. In the current research, column positions are fixed and raft thickness is to be reduced as much as possible. Hence these aspects are not given much importance. The projection of raft beyond the outer lines of boundary columns is a possible variable, which in the current research was restricted to a maximum of 1000 mm. Gupta (1997) compared the analysis results of rafts using conventional method and Winkler foundations and concluded that the former is generally on the conservative side. He also reported that bending moment in a raft may vary several times depending upon the raft size and soil properties under the raft. This variation increases further as the deviation from symmetry of the shape or loading of the raft increases. Though a variation from 10 kNm to 70 kNm in bending moment (BM) in a raft is an increase by 7 times, we are more concerned about the change required in the size of a member or area of steel. Such huge changes were not observed in any of the several cases studied in order to increase raft size or reinforcement substantially.

Folded plates are widely used in SS for spanning large areas. Due to its folding, bending moments are reduced, which reduces the required concrete and reinforcement for construction. Folding is done in straight lines and form work can be placed very easily. Material consumption can be considerably reduced in foundations with the use of shell type structures. An incidence of using folded plates in foundation was given by Martin (1959) for a 24 story building. The paper describes the construction aspects and cost advantage. In foundations, if the folding is done in such a way that steep slopes are not provided, then form work can be avoided. The construction of folded rafts are easy compared to beam and slab rafts and the additional space created at the basement level by folding a raft can be used for storage of water or for using as cable trenches. Hanna and Rahman (1990) investigated on the geotechnical aspects of triangular strip footings and concluded that there is 40 % increase in bearing capacity when such structures are used as foundations with a consequent reduction in settlement.

1.2 Objectives of study

The present paper compares the performance of folded plate and raft foundation under identical SS stiffness and loading. The flat raft was designed using Winkler method and then checked with continuum method. Folded plate foundation was also designed in the same way. There is uncertainty in the determination of k_s and E values and hence the impact of its variation over a wide range in the design of foundation and SS were studied. The final designs thus obtained for such a wide range of soil stiffness were compared for savings in materials and cost of execution. In addition the advantages of increasing fold height of raft and PR were studied.

1.3 Importance of the study

Considerable savings in concrete and steel can be achieved by folding a raft without a major increase in the labour required for its construction. The folded raft penetrating into the soil increases the stiffness of foundation due to increased folding depth. The space thus created can be used for the storage of water or passing the ducts. Large scale concrete filling is sometimes carried out on top of raft for getting the desired slopes or passing ducts. In a folded raft, it may be possible to reduce such filling and derive structural advantages of the shape. The increased substructure stiffness reduces settlement of raft and with several other benefits to substructure and superstructure.

2.0 Modeling And Structural Idealization

2.1 Winkler and continuum modeling

StaadPro (2008) and SAFE (2009) were used to model the Winkler Foundation. The plate load test at the proposed site yielded k_s of 25000 kN/m^2/m and this value is hereafter referred to as designated k_s. The analysis was carried out with and without the SS. The SS was modeled using line and plate elements and the substructure with quadrilateral plates. Several analyses were carried out taking typical situations. All designs were carried out using BS 8110 and BS 8007. Continuum modeling was carried out using Abaqus (2011), Plaxis 3D (2004) and StaadPro (2008). Solid elements were used to model the soil mass. In Abaqus and Plaxis, interface option is possible. In Staad Pro, perfect contact is assumed. In Staad Pro modelling, only E is varied. Mohr- Coulomb model was used for the study purpose in Plaxis and Abaqus as the present comparison is made for a site containing sandy strata. Mohr- Coulomb model in Plaxis requires 5 parameters as input namely the Cohesion (C), the angle of Internal Friction (θ), the Modulus of Elasticity (E), the dilatancy and the Poisson's ratio. Here the exact evaluation of E is very difficult and hence a range of values are taken consistent with the known soil properties. In this study the E values were varied from 15000 to 60000 kN/m^2 and θ from 30 to 43 degrees. A very small value of cohesion is given to aid computation as recommended in Plaxis 3D foundation user manual (2004). The recommended range of variation of E values is given in Table 2

(Bowles, 1997). Dilatancy value was given as zero and the Poisson’s ratio was varied from 0.35 to 0.4. Abaqus was used for comparing the results obtained for the folded plate with that of Staad. The comparison of designs were done between flat slab raft and folded raft. The rafts were analyzed for 43 service load combinations and 53 ultimate load combinations. M40 concrete and Steel of grade 460 was used. The raft consisted of 4 equal spans of 8 m in the X direction and 7m in the Y direction. Two projections, 0.3m and 1m of raft in X direction were considered in the present studies. Raft projection in the Y direction is kept at 0.3 m. A 3D view of the folded raft is given in Fig. 1. Folding is introduced in the X direction in such a way that the inclination of the surface is less than 32 degrees. The building is seven storied with column sizes of 600x600 mm. Seismic forces are generated as per UBC (1997) for zone 2A and soil classification Sc as demanded by the site features.

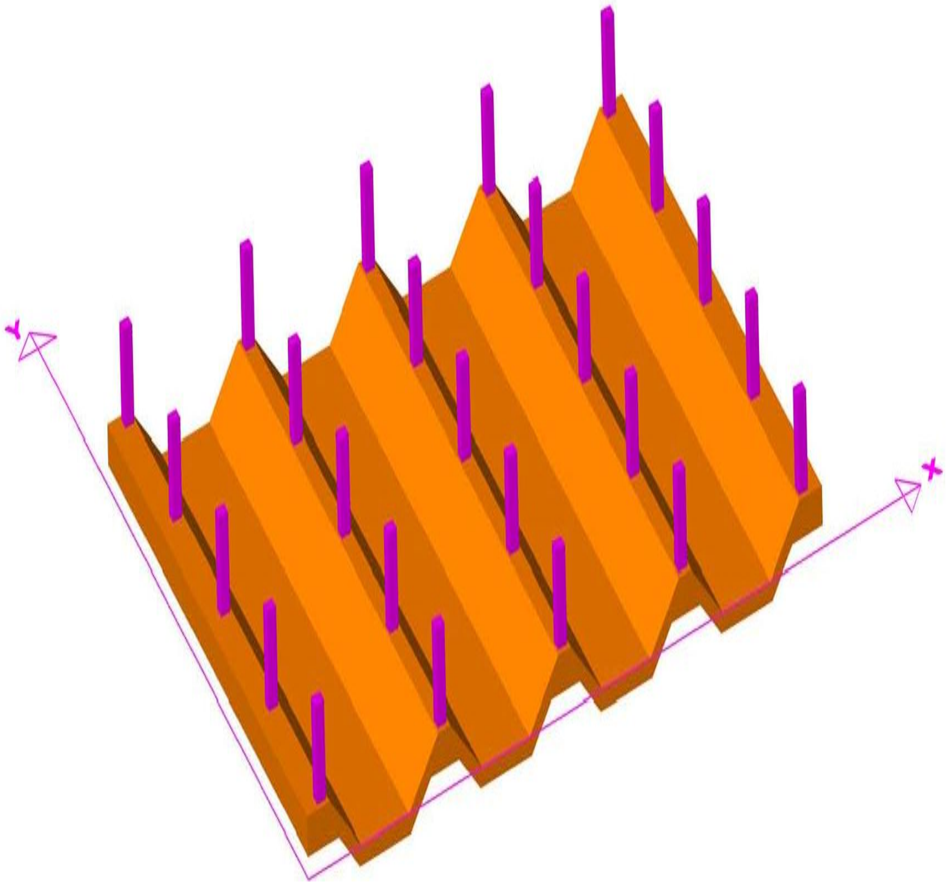


Fig.1 (a): 3D VIEW

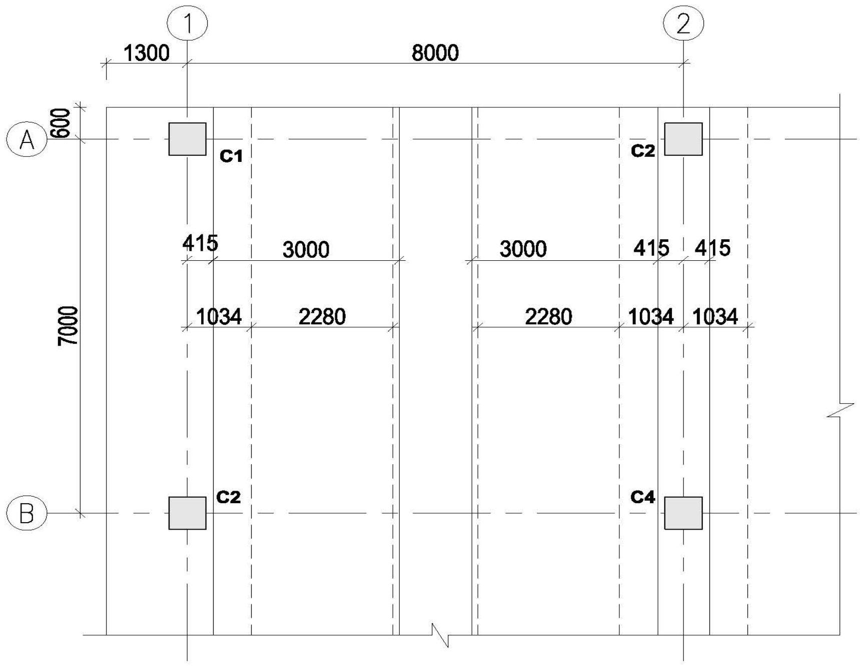


Fig 1(b) : PLAN VIEW

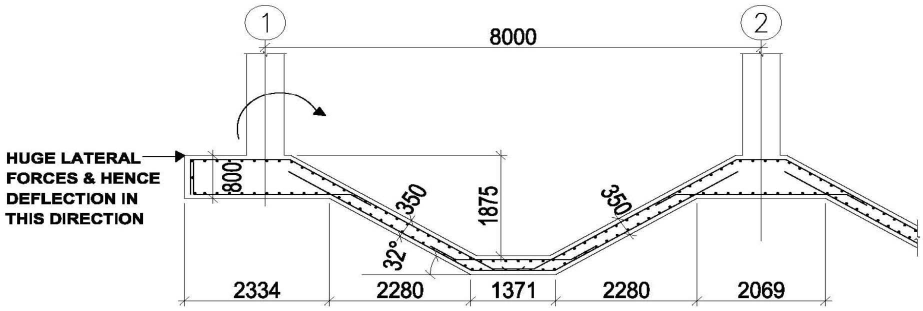


Fig 1(c): SECTION

Fig.1 : 3D View, Plan view and section of the raft folded in X- direction.

3. Analysis and Design Results

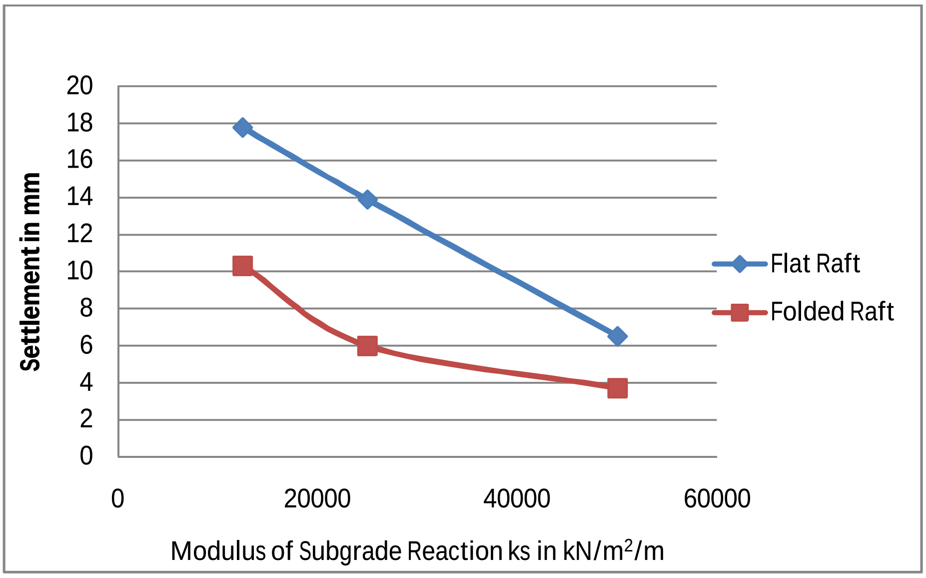
The flat and folded raft models were analyzed using Winkler soil model with 3 values of k_s (12500, 25000 and 50000 kN/m^2/m). The continuum analysis was carried out in two steps. In one step, E is the only variable with values of 15000, 30000 and 60000 kN/ m^2. In the second case, E and θ were varied for analysis with Mohr-Coulomb model. Analysis and design results are given in eight sub parts. Variation of base pressure, settlement below raft, BM in rafts, Shear and Impact of raft projections are covered in the first five parts. Part 6, contains the design of raft and folded plates. Part 7 deals with the impact of soil stiffness on SS design and the eighth part is a comparison of material and cost savings by folding the raft. In each section, a comparison on the performance of flat and folded plate foundations are given for Winkler and continuum modeling.

3.1. Variation of base pressure below the raft and the folded plates

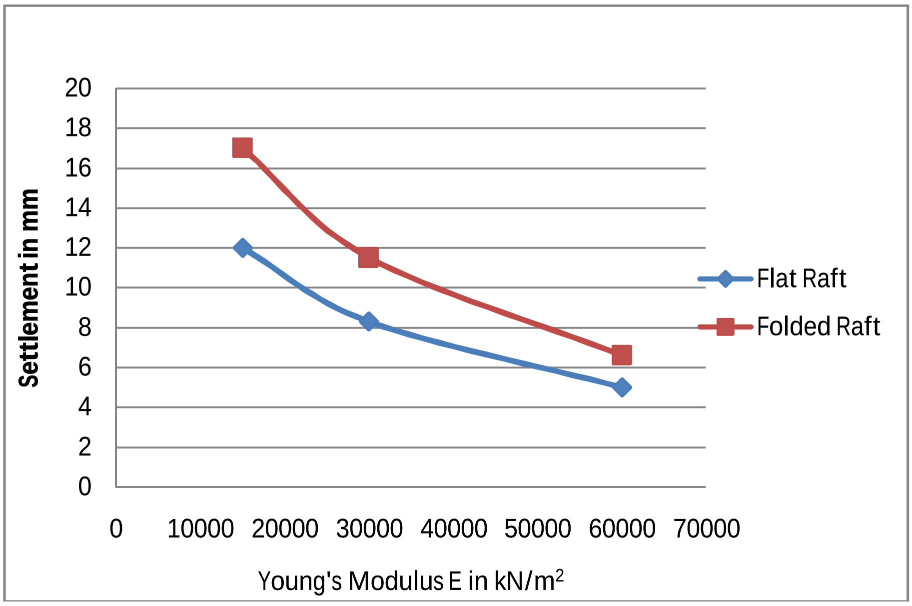
Base pressure below the raft was more under the column load transfer area. The maximum base pressure occurred under corner and edge columns, for smaller PR values. As PR increased, the area of raft increases and maximum base pressure below the raft is reduced significantly. At interior columns, the base pressure under column load transfer point and adjacent areas were almost uniform for low values of k_s. As k_s increases, the difference between maximum and minimum base pressure adjacent to the load transfer area also increased. The increase in k_s leads to load transfer through a small concentrated area below load point. The same trend was observed below the folded rafts with much less variation between the maximum and minimum base pressure anywhere. This may be due to the higher stiffness of folded raft distributing base pressure. Continuum modeling also gave similar results for both flat and folded rafts.

3.2 Comparison of settlement

The maximum settlement of the foundation was reduced as k_s increased (Fig 2a). When sufficient projections are provided all around the raft boundary from column lines, the raft may deflect in a dish shape with more settlement at the centre. This is due to higher loads likely at the middle area of the building. If PR is small, then the deflection pattern may change with maximum deflection at the edges or the corners. The maximum settlement of raft with a small projection beyond outer column line is less than that of raft without projection. The increase in PR leads to reduction in overall base pressure and lower settlement. When the analysis was carried out ignoring the SS stiffness, the settlement of the raft was slightly more compared to the raft analyzed along with SS, implying that the SS stiffness re-distributes base pressure and reduces settlement. Winkler analysis required around 1.5 m PR to get a dish like settlement below the raft. However 3D modeling showed dish like settlement even for 0.250 m PR. This may be due to the fact that the continuum models consider the strength of nearby soil at the edges. However for 0.25 m PR, as E and θ values were lowered, this settlement pattern is changing with maximum settlements at the edges with concentration of stresses there. In Fig 2b, the maximum settlement is more below folded raft in continuum method compared to flat raft. This is due to the very high lateral forces applied and consequent lateral displacement at the supports of corner and edge columns in X direction (Fig.1c). At the edges, in the case of raft foundations, the lateral forces are taken by friction between raft and soil. In the case of folded rafts, the soil applies lateral force on the folded portion and hence significant lateral displacement occurs.



(a) Winkler Method



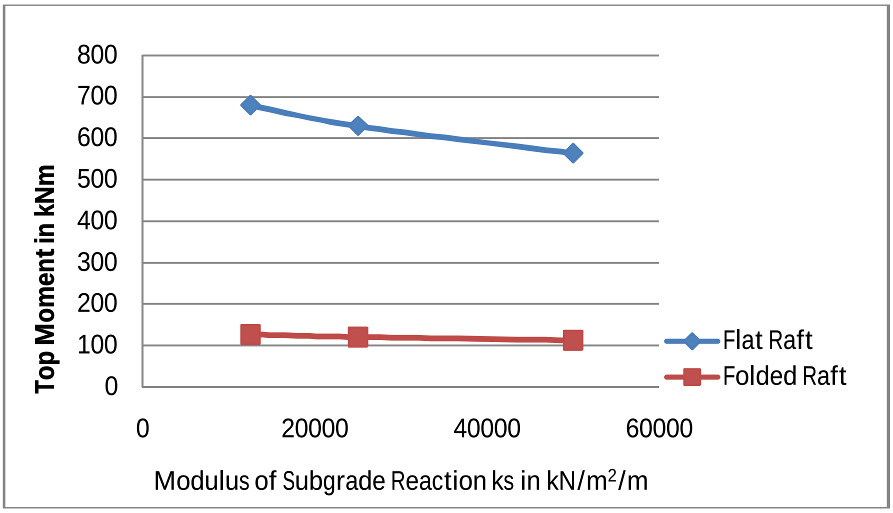
(b) Continuum Method

Fig.2: Variation of maximum settlement below flat and folded rafts with k_s or E values

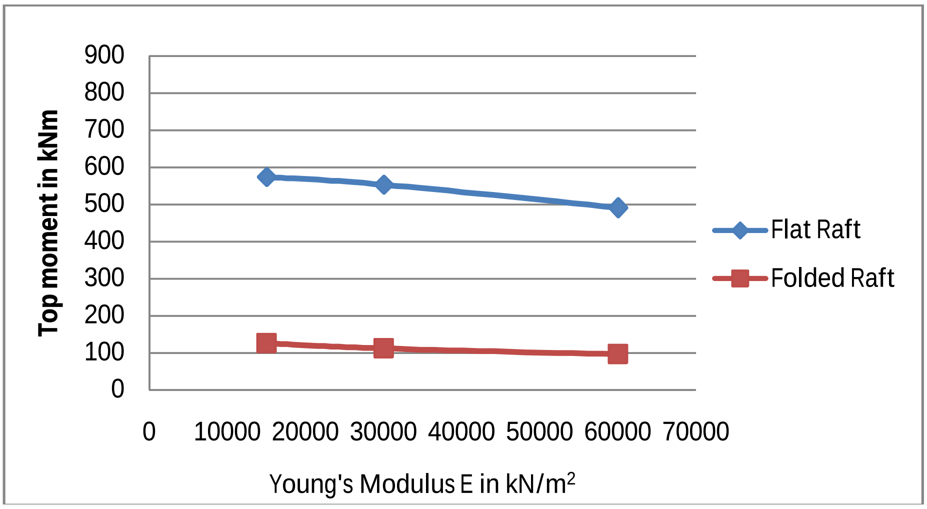
In Winkler method, the horizontal movement is arrested in modeling itself and hence overall settlement is less. Hence in Fig.2a, the settlement of folded raft studied using Winkler method is less. In general the settlement computations are never accurate and differential settlement is to be given more consideration. The settlement of folded raft reduces as its fold height (or fall from horizontal plane) increases due to the increased stiffness.

3.3 Variation of maximum design moments

The maximum value of bottom moments at the face of columns in the raft is taken as the design bottom moment in a raft. As k_s increases, the maximum bottom and top moments are reduced (Fig. 3a and 4a). Continuum modeling also showed similar trends (Fig3b and 4b). If the SS stiffness is ignored in the calculations, the maximum top moment increases. The BM values are considerably reduced due to the folding. The maximum BM in X direction (Mx) was reduced by 80% at the top and 70 % at the bottom. In y direction also, maximum top moments (My) were reduced by 50%. The bottom My moments were reduced by 40%. The effect of My moments are concentrated along the thick flat portion supporting the columns and it is very small in the fold part. The reinforcement for My needs to be placed like that of a beam and hence it considerably reduces the reinforcement required for the entire raft, compared to the flat raft. Though it is not possible to find an exact relation between k_s and E, it can be concluded that in the range of k_s and E studied, the bottom maximum bending moments for the raft are slightly on the higher side in continuum modeling. The top maximum moments were nearly 10 % less than the Winkler results. For folded rafts, the continuum methods showed similar trends with reduction of 67% for the top moment in X-direction. Bottom moment (Mx) was reduced by 50%. The top bending moment Mx in the fold portion was reduced by 80% and goes on reducing with increase in fall of fold portion. BM in y direction is concentrated in a narrow width of folded raft supporting the columns and for the rest of the area BM was reduced by 90%. In general, the moment values are more at top and bottom in X and Y directions compared to the Winkler model. Fig. 3 and 4 shows variation in moment in the X direction only.

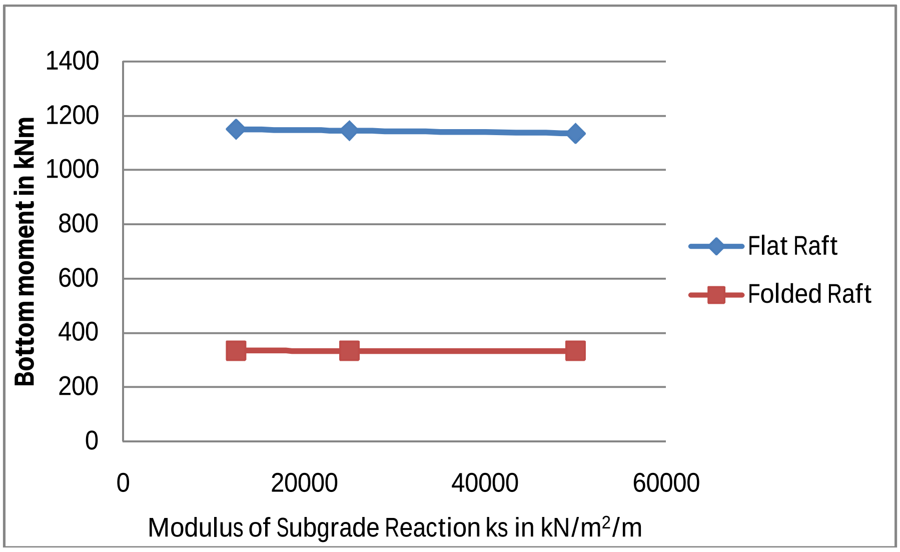


(a) Max. top moment by Winkler Method

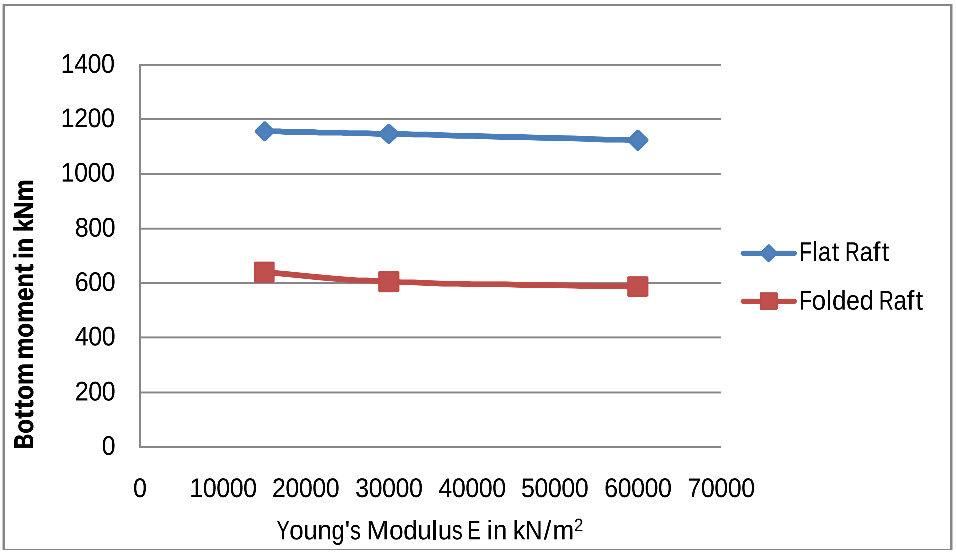


(b) Max. top moment by continuum Method.

Fig.3. Variation of bottom maximum BM in folded and flat rafts using Winkler and continuum methods.



(a) Max. Bottom Moment, Winkler Method



(b) Max. Bottom Moment, Continuum method.

Fig.4. Variation of bottom maximum BM in folded and flat rafts using Winkler and continuum methods.

The increase in fall of the folded portion increases the stiffness and reduces settlement and which in turn reduces BM and reinforcement in a raft.

3.4 Influence of shear

The thickness of the raft is increased for a small area supporting the columns for the folded raft as shown in Fig. 1. No other special care was required in comparison to the flat rafts.

3.5. Impact of projections of the raft beyond the outer line of boundary columns

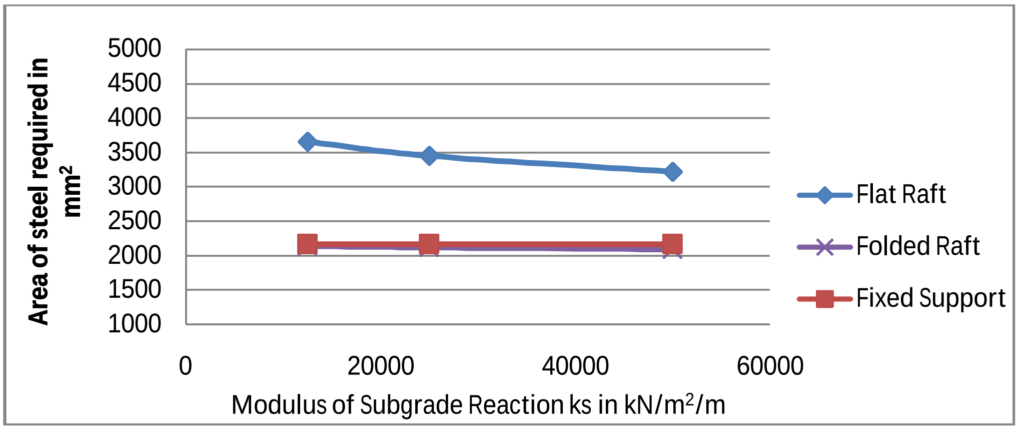
If PR is very small, the top moments in the raft in the spans adjacent to edges may increase much more with decrease in k_s. The reinforcement required for bottom moments are concentrated near column supports and the quantity required for the same is low even if the variation in moment is more. However the influence of increase in top moment is felt over a large area and it increases the quantity of reinforcement required considerably. By providing projections to the raft, some other advantages were also observed. There was a reduction in the total and differential settlements with change in deflection pattern and reduction in reinforcement in the substructure and SS. The studies on folded rafts with continuum model also gave similar beneficial results of PR. Projection in the fold direction (X direction) reduces the settlements considerably. The effect of Projection in Y direction is much less as far as settlement is concerned.

3.6 **Design of Flat and folded Rafts**

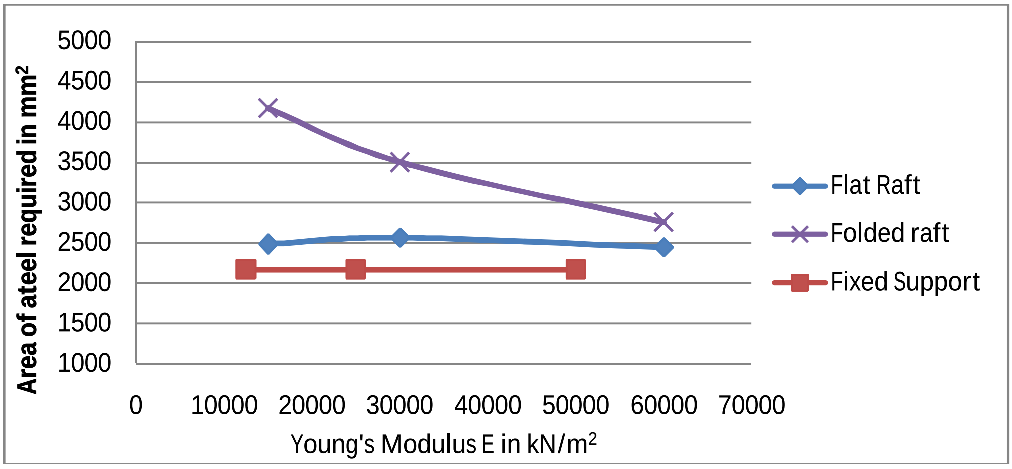
Minimum reinforcement was decided considering the crack width limitations. For 900 mm raft the value of this moment is 375 KNm for Service load in main direction and 325 kNm for secondary moment for a reinforcement of 20mm@ 200 mm c/c, for a crack width of 0.3mm. Similarly the other ranges are worked out for different diameters of extra bars to be provided like 20@200 mm c/c, 25@ 200 mm c/c etc. After finding out ranges of BM for different combinations of reinforcements, the raft BM at different locations were grouped in to these ranges and reinforcement was provided accordingly. Then the raft was investigated for one way shear and punching shear. At few locations, the bottom reinforcement is increased to give additional shear capacity for avoiding shear links. After completing the reinforcement design, the raft was further analyzed changing the k_s values to 12500 KN/sqm/m and locations where reinforcement requires modification were identified. Then analysis was repeated after varying the k_s to 50000 Kn/m ^{2}/m and design was reviewed. Then reinforcement detailing is carried incorporating all the cases of maximum moments and total quantity was worked out. Then the design was checked for continuum modeling. There was no increase in reinforcement required for variation in k_s, may be due to the symmetry of the structure. Checking using Continuum method resulted in an increase of 1% reinforcement. For folded rafts, the same design procedure was followed, though the reinforcement required and ranges of moments were different. The thickness of folded portion is 350mm and it is more at column supports. The folded portion is subject to much less moments and hence much less thickness and reinforcement were needed. The impact of varying k_s values from half to two times the designated value was found to be insignificant as far as structural design was concerned. However continuum modeling required more reinforcement upto 9%. This showed the need for modifying the Winkler Method giving consideration to the stiffness of soil.

3.7 **Impact on SS design.**

For Winkler model, it was observed that the column reinforcement decreases with increasing k_s values for both flat and folded rafts (Fig.5a). Beam bending moments were also reduced throughout the building with increase in k_s though the variation was negligible. Continuum analysis of flat rafts also showed similar results. However folded rafts required more reinforcement for edge and corner columns at Ground floor (Fig.5b). For the interior columns, less reinforcement was required compared to flat rafts. Folding of foundation reduces the maximum reinforcement requirements compared to equivalent flat raft in all cases whether it is with continuum or Winkler modeling except for few corner and edge columns and some beams at the ground floor level. It is also seen that the column designs by Winkler methods or with fixed end condition are not the maximum values for all columns as shown (Fig. 5a and 5b). Sometimes assuming fixed support to the columns may give the least reinforcement which means that designs may not be safe and hence soil structure interaction studies need be carried out in all cases. (Fig.5a, 5b). In Fig. 5b, the reinforcement for ground floor corner columns were much more for folded raft compared to flat raft in continuum method which means that even Winkler method of soil structure interaction is not conservative. Fig. 6a shows the variation in maximum BM for an outer beam using Winkler method for folded, flat rafts and a structure with fixed column supports. Similarly Fig. 6b shows the variation for continuum method and generally BM reduces for beams of the structure supported by folded plate foundation. If PR is considerable, then SS design is also affected. Column reinforcements are reduced. Beam bending moments and settlements are also reduced. The impact of folding the raft is felt over the entire structure. As the central fall of fold increases, BM was reduced in the raft with reduction in settlement. This influences the design of columns with reduction in reinforcement. Beam bending moments were reduced throughout the structure.

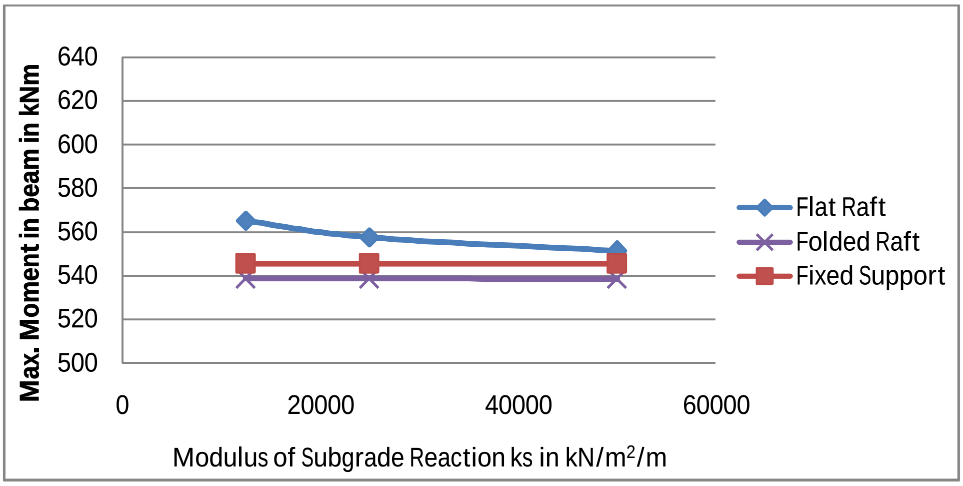


(a) Winkler method, Variation in a corner column reinforcement.

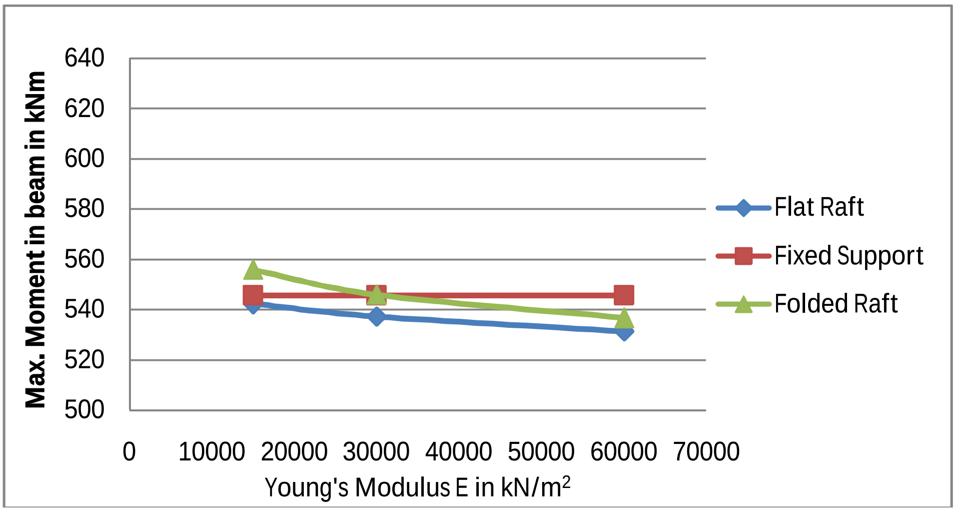


(b) Continuum method, Variation in a corner column reinforcement.

Fig.5.: The variation in reinforcement for the GF corner column in Winkler and continuum method.



(a) Winkler method, variation in a ground floor beam factored top moment.



(b) Continuum method, variation in a ground floor beam factored top moment.

Fig.6: The variation in a GF beam BM in Winkler and continuum method.

3.8. Comparison of material consumption and cost of execution.

The flat slab raft and folded plate raft designed considering the likely variations in k_s and E values were compared for material consumption and cost of execution. Concrete consumption was reduced by 40% and steel consumption by 30%. The savings in SS design were ignored. The overall cost reduction was nearly 35%. With increase in fall of the folded raft, the material consumption further reduces.

4.0 Conclusions

A raft and folded plate foundation were designed for varying k_s values from half to two times the designated values. There was no increase in reinforcement required in both cases. The designs were checked by continuum method and there was an increase in reinforcement for the flat raft by 1% and folded raft by 9%. Designing the raft for such a range of k_s or E values gives added confidence at a small additional expense. Maximum top and bottom moments were found to reduce with increase in k_s for both flat and folded plate foundations. Column reinforcement required reduces as k_s increases. Similarly the bending moments were reduced for the beams throughout the building as k_s increased, the variation being very small. Between folded and flat rafts, folded raft structure requires slightly lower reinforcement for columns and beams. Raft projection beyond outer column lines brings significant changes to top moment values in the raft. Column and beam reinforcement were slightly reduced when raft projections were more. It also reduces reinforcement required and settlement of both flat and folded raft. Continuum methods show similarity in the BM values obtained with those computed using k_s with slightly higher maximum moment at bottom and lower values at top in the case of flat rafts. In the case of folded rafts, top and bottom maximum moments are reduced in continuum method also. However even the reduced values are much more than that obtained from Winkler method. In continuum method, the settlements under corner and edge columns were more in folded rafts especially when the raft projections were low. This is found to be due to the heavy lateral loads at those supports and due to which folded raft was deflecting in the fold direction. This increases the reinforcement in the outer spans of fold area of folded raft and its corner and edge columns at ground floor level. In general Winkler method is sufficient for the design of flat rafts and in the case of folded plates, lateral stiffness of soil needs to be considered in the analysis. The column designs obtained by giving fixed supports to the columns and sometimes even Winkler method may not give a conservative design pointing the need for elaborate soil structure interaction studies including continuum analysis for important structures. The designs of folded plates are affected by the central fall. With increase in the fall, reinforcement can be considerably reduced. The concrete can be reduced by 40% and steel by 30% without any additional formwork for concreting. As the fall of the folded raft increases, settlement reduces due to the increase in stiffness of foundation. Reinforcement required in folded raft also reduces. Similarly column and beam reinforcement required was slightly lower compared to the one with less fold height. Significant cost reduction of 35% can be achieved in raft construction by folding the raft without considering other benefits like space saving and the advantages obtained in superstructure design.

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