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The paper was published in the proceedings of the 7th Australia New Zealand Conference on Geomechanics and was edited by M.B. Jaksa, W.S. Kaggwa and D.A. Cameron. The conference was held in Adelaide, Australia, 1-5 July 1996.
Behaviour of Stiffened Raft Foundations

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Summary: In this paper, the behaviour of raft foundations subjected to relative ground movements due to swelling or shrinking soils is analysed and discussed. The differential settlements and the maximum moments are analysed for different raft stiffnesses in conjunction with the free-field soil movements. The influence of stiffened beams in restricting the differential settlement is discussed and the results are presented for the central and edge heave conditions. A non-linear approach is adopted to undertake the analysis of stresses at the soil-slab interface. A computer program RSTIFF, based on the finite element technique, is used to carry out the analysis. The paper is generally focussed on the benefits of the structural strengthening of raft, emphasising its settlement restricting features. Finally, curves are presented to estimate the differential settlements and their corresponding moments for both unstiffened and stiffened rafts for various free-field soil movements.

1. INTRODUCTION

The behaviour of foundations on swelling and shrinking soils has been a challenge for practising engineers. The ground surface, which is flat at the time of laying the foundation slab, develops vertical surface movements due to the change in the moisture content. This alters the ground support condition underneath the slab and may induce excessive differential settlement & moments into the slab beyond acceptable limits. There have been numerous cases of structural damage due to these effects. In order to overcome this problem, various methods have been adopted to restrict the moisture variation of the soils underneath the foundation. Some of these methods are discussed below in terms of their overall performance and effectiveness.

(i) Provision of thin slabs around the periphery of the main structure may be provided as a barrier to the penetration of moisture to the soil underneath the slab, in order to restrict the moisture variation. This may not be very effective on a long term basis as any crack into the peripheral slab may allow water penetration into the founding soil.

(ii) A cut-off around the structure may also be considered as the potential barrier to the moisture transfer into the founding soil from outside, but any domestic leakage such as leaky pipe or drainage etc may cause penetration of water into the founding soil, resulting in heave formation.

Other methods such as maintaining the moisture content of the soil constant in the proximity of the structure may also control the ground movement. It should be noted that these methods would require attention on a regular basis and their performance would depend on various unexpected and unprecedented problems such as local water logging.

Instead of controlling the moisture content of the founding soils, the concept of strengthening the slab structurally to cater for the uneven ground support, has been found to be an effective and dependable solution to this problem. The foundation slab is stiffened enough to withstand the relative ground support condition and to reduce the differential settlement to an acceptable limit. In this paper, the behaviour of such slab foundations is analysed and discussed in order to provide a wider spectrum of understanding.

This paper outlines the problem into two categories as:

i) defining a soil profile underneath the raft due to swelling or shrinking of soils and

ii) the interaction of the soil with the foundation to estimate the additional induced moments and differential settlements due to the relative ground movement.

The objective of this paper is to outline the influence and benefits of stiffened beams and the beam configuration in restricting the differential settlement and the subsequent effect on the maximum moment.

2. ANALYSIS

In the analysis, the raft is considered as a plate resting on a homogeneous and semi-infinite mass. The plate is discretised into various elements and nodes and is analysed by using the finite element technique. The raft elements correspond to uniform blocks of reaction, which are used to compute the
deflection. The deflection is specified in the vertical direction. The analysis is carried out neglecting the membrane forces. The elements are four-noded rectangular shaped with 16 degrees of freedom. The variables at each node consists of vertical displacements, rotations in x & z directions and twist. The influence factors for the raft elements & the soil are determined and coupled, so as to satisfy displacement compatibility. The influence factors for the raft are obtained by pinning the raft at the centre. The mathematical formulation is briefly illustrated below. For the raft:

\[ \delta_r = I_r(-P) + aA + \delta_q \]  

(1)

where,

- \( I_r \) = Raft influence matrix
- \( a \) = \((1, 1, 1, \ldots, 1)^T\)
- \( \delta_r \) = Deflection under raft element
- \( P \) = Stresses under raft elements
- \( \Delta \) = Translation for pinned condition
- \( \delta_q \) = Deflection at the centre of each raft element for pinned condition.

The soil profile adopted for the analysis is shown in Figure 2. This will introduce the relative ground movement \( \delta_s \) underneath the raft elements. The soil displacement may be expressed as:

\[ \delta_s = I_s P + S_i \]  

(2)

where,

- \( I_s \) = Soil Influence matrix
- \( S_i \) = Vector of free field soil movement

The soil and the raft displacements are equated in order to satisfy the displacement compatibility:

\[ \delta_s = \delta_r \]  

(3)

Therefore, equating equations (1) & (2), it may be expressed as:

\[ [I_s + I_r]P - aA = \delta_q - S_i \]  

(4)

The above mathematical model is analysed for the raft-soil system and solved for the contact stresses. These stresses are used to estimate the displacements and moments at various points of the raft.

A non linear approach is adopted to carry out the analysis of stresses at the raft-soil interface. In order to do so, the effect of separation between the soil & the raft and local yielding of soil underneath the raft are considered in the analysis. The relative stiffness of the raft is considered as:

\[ k_R = \frac{4E_R I_R^3 B_R \left( 1 - \nu_s^2 \right)}{3\pi E_s L_R^2} \]  

(5)

where,

- \( E_R \) and \( E_s \) = Concrete and Soil moduli
- \( I_R \) = Raft thickness
- \( L_R \) and \( B_R \) = Length and width of the raft
- \( \nu_s \) = Poisson’s ratio of the soil

The accuracy of the program output for a strip footing was verified with the results of Poulos (1984) and found to be in good agreement.

3. FREE FIELD SOIL MOVEMENTS

In the event of seasonal moisture variation, clay soils change in volume and are subject to vertical as well as horizontal movement. The presence of an impermeable surface or slab on the expansive soil will alter the pattern of seasonal soil moisture change. If the slab is placed in the dry condition, the soil along the edge of the slab will be more exposed to wetting compared to the central part and will result in an edge heave formation (Fig 1c). Conversely, a slab placed on a wet ground condition will subject to drying along the edge of the slab and will experience a central heave formation (Fig. 1b).

The AS 2870.2 (1990) indicates that the response of reactive clay to the moisture change is a complex phenomenon and the surface movement prediction involves estimation of suction and instability indices. Laboratory tests should be undertaken to estimate the instability index to represent the clay reactivity and the suction profile to represent the design moisture change. The code also recommends the further details outlined in Cameron (1989), Mitchell & Aivalle (1984) and NSW Builders Licensing Board (1985).
In this paper, a “non-linear soil structure interactive approach” is adopted to carry out the analysis, including the effect of load redistribution due to the separation at the soil-raft interface. The ground movement is defined as a vector \( S_j \).

In order to define the soil profile, a polynomial, as suggested by Lytton (1970), is adopted as below:

\[ y = c x^m \]  

(6)

where,
\( y \) = vertical soil movement at \( x \) (Fig. 2)
\( x \) = distance from the centre of the raft (Fig. 2)
\( m \) = integer exponent (mound shape index)
\( c \) = a constant.

For the central heave, the soil movement \( S_o \) occurs at the corner of the raft (Fig. 2b) and substituting this to equation (6), it may be obtained as:

\[ y_c = S_o \left( \frac{y}{L_R} \right)^m x^m \]  

(7)

where,
\( y_c \) = \( y \) values for central heave

For edge heave formation, \( y \) is expressed as:

\[ y_e = -y_c \]  

(8)

The constant \( c \) in equation (6) is dependent on \( S_o \) or \( y_m \) (as mentioned in AS 2870.2). The computer model RSTIFF undertakes the analysis by combining the soil profile and the raft, including the interaction and non-linear effects. The final soil mound is deformed due to the presence of raft and is dependent on the soil-structure interaction effect.

The analysis in this paper is carried out with the heaves as defined in equations (7) & (8), including the effect of twisting. Although, the mound index \( (m) \) is dependent on various soil parameters, \( S_o \) and other conditions, but for the purposes of this paper, a constant value of 2 is adopted, which represents a parabolic mound underneath the raft. In other words, the mound is parabolic in all direction from the centre of the raft. The value of \( y \) is directly related to \( x \), therefore the maximum value of \( y (= S_o) \) will occur at the maximum value of \( x \), i.e. at the corner of the raft, as indicated in section (Fig. 2a). It should be noted that various mound index values will influence the moments and displacements in the raft and has a potential for further investigation.

4. DESCRIPTION OF CASES

The analysis is carried out with two types of beam-slab arrangements (Config. I & II) as indicated in Figure 3 & 4. Config.II consists of a greater number of beams compared to Config.I. The objective of adopting two types of configuration is to present the influence of the number of beams and their configuration on the differential settlement and moment. The arrangement for both the configurations is indicated below:

![Figure 3. Configuration - I.](image)

![Figure 4. Configuration - II.](image)

The above cases are analysed for the central as well as for the edge heave conditions.

5. PRESENTATION OF CURVES

The notation used to represent the curves in Figures 5 and 6 are as follows:

- \( \Delta_{st} \): Differential settlement between the centre & corner of the stiffened raft
- \( \Delta_s \): Differential settlement of unstiffened raft
- \( M_s \): Maximum moment of unstiffened raft
- \( M_{st} \): Maximum moment in stiffened raft
- \( t_b \): Stiffened beam thickness
- \( t_s \): Raft slab thickness (= \( t \), used elsewhere)
Figure 5. Stiffened raft behaviour (central heave).

Figure 6. Stiffened raft behaviour (edge heave).
δ_r : Relative reduction in differential settlement due to stiffening effect
δ_m : Relative increase in moment due to stiffening effect.

6. RESULTS OF ANALYSIS

A 10m by 10m square raft, subjected to a maximum free field soil movement of 100mm (S_o) is considered for the analysis. The analysis is carried out with the configurations described in section 4, incorporating the effect of lift off and local soil yield at 300kPa underneath the slab. The Young’s moduli of raft and soil are adopted as 20,000 MPa and 10 MPa respectively. The Poisson’s ratio of soil is considered as 0.3. The concrete cross-section is adopted as uncracked for the analysis and the shear stresses are assumed to be not significant. The width of the beam is adopted as 300 mm with 0.2% reinforcement.

The differential settlements and the maximum moments of the unstiffened slab are compared with the stiffened slab for both central and edge heave conditions. The depth of the stiffened beams is varied and its effect on settlements and moments are presented and discussed.

It can be seen from the Figures 5(a) and 6(a) that the differential settlement of the rigid unstiffened raft is negligible and increases as the raft tends to become more flexible. The moment is higher in the case of a rigid raft and reduces with the reduction in the raft stiffness (Fig. 5b, and 6b). The differential settlement factor (Δr/S_o) is observed to be unity for a very flexible raft. In other words, the deflected shape of the raft follows the profile of the soil underneath the foundation, causing maximum differential settlement.

The differential settlement of the raft may be reduced by incorporating stiffened beams at strategic locations, creating a bridging action on the heave. In the presented curves, the factor δ_r is indicated as the relative reduction in the differential settlement because of the stiffened beams. It can be seen from figures that configuration II provides a better stiffening effect than configuration I, because of the number of beams and their configuration.

As expected, Config. II is more effective in reducing the differential settlement compared to Config. I. It can also be seen in Figures 5d and 6d that the increase in moments is less for Config. II than for Config. I.

The reduction of the differential settlement is also influenced by the depth of the beams (Fig 5c and 6c). An increase in the beam depth reduces the differential settlement and increases the moment. It may be observed that after a certain value of K_r, there is no further reduction in the differential settlement with increase in the slab stiffness. This may be defined as a limit beyond which the rigidity of the slab itself is enough to restrict the differential settlement and the further increase in the beam depth has no influence in the raft. It is understood that the differential settlement is not a critical issue for higher K_r values. In the presented curves, the factor δ_m is indicated as the relative increase in the maximum moment with respect to M_s, due to the increase in the beam depth.

The maximum settlement occurs at the corner of the raft in the case of the central heave, whereas for the edge heave condition it occurs at the center of the raft. The moments are negative for central heave and positive for the edge heave condition.

7. ESTIMATION OF DIFFERENTIAL SETTLEMENT AND MOMENT

Previous analyses were carried out to demonstrate the stiffened raft behaviour for the maximum soil free field (S_o) as 100 mm. In order to estimate the

![Figure 7. Curves for a uniformly loaded 10m×10m raft for Config. I.](image-url)
differential settlements and their respective moments for a wide range of ground movement, analyses are carried out with various $S_n$ values for configuration I & II and the results are presented in Figures 7 and 8. These curves also provide an indication of the influence of the $T_y/T_x$ ratio on the differential settlement. It can be seen that the moment is positive when the raft is resting on flat ground (i.e. $S_n = 0$) and reduces when subjected to shrinking soils (Central Heave) and changes to negative beyond a point. In contrast, in case of swelling soils (Edge Heave), the moment is always positive.

It can be inferred from these curves that the differential settlement may be reduced either by increasing the beam depth or by adopting a different configuration, consisting of more stiffened beams. The approximate differential settlement values for any intermediate $T_y/T_x$ ratio may be obtained by interpolation.

8. CONCLUSIONS

The analysis indicates the following characteristics:

i) Increase in the raft stiffness leads to larger moments and smaller differential settlements.

ii) Stiffening the raft adequately is a suitable & dependable solution to cater for the relative ground movement.

iii) Differential settlement of raft slab may be reduced by introducing stiffened beams at strategic locations.

iv) To achieve further reduction in the differential settlement, either a higher slab stiffness ($K_p$) in conjunction with stiffened beams or a different slab beam configuration with a greater number of beams may be adopted.

v) Increase in beam depth causes reduction in differential settlement and increase in the maximum moment.

vi) Moments in the Config.II due to the free field soil movements are less compared to Config.I, because of the “sharing effect” among the greater number of beams.

vii) A non linear soil structure interactive approach should be adopted to analyse the raft on swelling or shrinking soils. The analysis should be carried out, including the effect of rotation and twist.

9. REFERENCES

