Analysis of Soft Ground Reinforced with Granular Piles: II Effect of Stiff Crust

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1. INTRODUCTION

For low rise buildings and structures such as liquid storage tanks, abutments, embankments, etc., that can tolerate some settlements, granular piles provide an economical method of support in compressible and fine grained soils (Mitchell, 1981). By virtue of their strength and stiffness, the granular piles carry substantially greater proportion of the applied loads with a relatively smaller amount of deformation as compared to the in-situ soft soil deposits. The columns of granular material also help to speed up consolidation process in the soft ground and hence as a consequence, the post construction settlements of the structure built on them would be smaller. Moreover, the in-situ stress conditions get improved due to the installation of granular piles, e.g., the lateral stresses around the inclusionstend to be higher than the at rest values. Granular inclusions, if installed in loose sands, minimize the likelihood of liquefaction of these deposits due to earthquakes because of their tendency to dilate while shearing and also, to dissipate the excess pore pressures generated (Mitchell and Huber, 1983; Okita et al., 1991; etc.). Granular piles are cost effective and can be installed rapidly using vibro-replacement, composer or rammed stone columns techniques (Madhav, 1982) and even by heavy tamping (Van Impe and De Beer, 1983).

However, the success of granular pile treatment depends mainly on its adequate reduction of overall foundation settlements with respect to those of untreated ground. The amount of load the granular pile reinforced ground can carry depends on the nature of soft soil, the material used for and the stiffness of the granular pile, thickness of the granular mat laid on top, etc. Several empirical and rational approaches are available to estimate the reduction in settlement due to installation of granular piles. Poorooshasb et al. (1991) suggested that a rational design of granular piles must account for the performance of the system as a whole, i.e., it must consider such processes as consolidation, settlement, load sharing, etc., simultaneously at any loading stage. In an attempt to develop a rational design approach for granular pile reinforced ground with granular pad or mat on top, Shahu et al. (1998) proposed an approach based on interface shear stress transfer mechanism. This paper is an extension of previous approach (Shahu et al., 1998) and incorporates the effect of stiff crust on top of the soft soil in the analysis. It is common knowledge that bulging and subsequent failure of the granular pile occurs mainly due to high stress concentration near top of the granular pile (within a depth of one or two diameters). However, the presence of stiff crust on top is expected to alter the stresses significantly at this level. Hence, it is important that the effect of crust be incorporated in the analysis so that the actual stress concentration within top few meters of the reinforced ground can be predicted accurately. In the present analysis, the crust is considered to behave as an overconsolidated soil with a uniform preconsolidation pressure (or yield stress) equal to atleast the overburden pressure due to the total crust thickness. However, the maximum yield pressure needs to be evaluated accurately by laboratory consolidation tests and the test results should be used for the actual predictions. Solution is obtained by imposing the displacement compatibility at soil-granular pile interface. Evaluations are made to examine the influence of various parameters such as thickness of the crust, the ratio of swell index to compression index for the soil in the crust, etc., on stress and displacement response of the reinforced ground, and on the stress transfer between the granular pile and the soil.

2. FORMULATION AND SOLUTION

Details of a unit cell incorporating the stiff crust is shown in Fig. 1. The formulation presented in Shahu et al. (1998) has been extended for the case with the stiff crust in this paper. If h_c is the thickness of the stiff crust and γ_{sub} is the submerged unit weight of the soil, then the preconsolidation pressure or yield stress, σ'_c of the stiff crust is

$$\sigma'_c = \gamma_{sub}\, h_c \tag{1}$$

The unit cell is discretized into n equal number of elements to predict the stresses, displacements and shear stresses at different depths of the reinforced ground. For any given element 'i', the average stresses at the midheight in the granular pile and the soft soil are q_{gpi} and q_{si} respectively. Equilibrium of vertical forces at any depth can be expressed as

$$q_o = q_{gpi} A_r + q_{si} (1 - A_r) \quad (2)$$

where q_o = applied stress on the unit cell; and $A_r = (d / d_e)^2$, d and d_e being the radii of the granular pile and the unit cell, respectively. The displacement of any element 'i' of the granular pile is

$$\Delta S_{gpi} = \frac{q_{gpi}}{E_{gp}} \Delta h_i \quad (3)$$

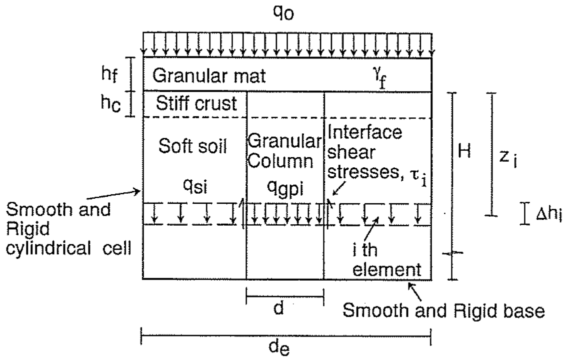

Fig. 1 Unit cell and the definition of the termms used

where ΔS_{gpi} = displacement of the granular pile at the ith element; Δh_i = thickness of ith element; and E_{gp} = modulus of deformation of the granular pile. The displacement of stiff crust surrounding the granular pile for the ith element within the stiff crust is obtained as

If$(\sigma_{oi} + q_{si}) > \sigma'_c$, then

$$\Delta S_{ci} = 0.434 \frac{C_s}{(1 + e_o)} \Delta h_i \ln \left(\frac{\sigma'_c}{\sigma_{oi}} \right) + 0.434 \frac{C_c}{1 + e_o} \Delta h_i \ln \left(\frac{\sigma_{oi} + q_{si}}{\sigma'_c} \right) \quad (4)$$

and, if $(\sigma_{oi} + q_{si}) \leq \sigma'_c$,then

$$\Delta S_{ci} = 0.434 \frac{C_s}{(1 + e_o)} \Delta h_i \ln \left(1 + \frac{q_{si}}{\sigma_{oi}} \right) \quad (5)$$

where ΔS_{ci} = displacement of the crust at a depth, z_i; C_c = compression index of soil; e_o = initial void ratio; σ_{oi} = effectiveoverburden stress at the center of ith element; and C_s = swell index of the crust. After normalization with $\sigma'_{av} = (H/2)$, Eq. (1) reduces to the following form:

$$\sigma^*_c = 2h^*_c \quad (6)$$

where $h^*_c = \frac{h_c}{H}$ = normalized crust thickness; and H = total depth of granular piles. Asterisk over the stress parameters indicates normalization with σ'_{av}. Similarly, after normalization with σ'_{av}, Eq. (3) can be rewritten as

$$\frac{\Delta S_{gpi}}{H} = \frac{q^*_{gpi}}{E^*_{gp}} \frac{\Delta h_i}{H} \quad (7)$$

where $E^*_{gp} = \frac{E_{gp}}{\sigma'_{av}}$. After substituting the following relationship,

$$R_c = \frac{C_s}{C_c}$$

and normalizing the stress parameters with σ'_{av}, Eqs. (4) and (5) can be rewritten as:

If $(\sigma'_{oi} + q^*_{si}) > \sigma^*_c$, then

$$\frac{\Delta S_{ci}}{H} = \left(\frac{R_c}{C_l}\ln\left(\frac{\sigma^*_c}{\sigma^*_{oi}}\right) + \frac{1}{C_l}\ln\left(\frac{\sigma^*_{oi} + q^*_{si}}{\sigma^*_c}\right)\right)\frac{\Delta h_i}{H} \tag{8}$$

and, if $(\sigma^*_{oi} + q^*_{si}) \leq \sigma^*_c$, then

$$\frac{\Delta S_{ci}}{H} = \frac{R_c}{C_l}\frac{\Delta h_i}{H}\ln\left(1 + \frac{q^*_{si}}{\sigma^*_{oi}}\right) \tag{9}$$

where $C_l = \frac{(1 + e_o)}{0.434\ C_c}$ = soil stiffness factor. The effect of the granular pad or mat is taken into consideration by taking the value of σ^*_{oi} as given below:

$$\sigma^*_{oi} = 2Z^*_i + f_s \tag{10}$$

where $z^*_i = z_i/H$; $f_s = (\Upsilon_f\ h_f\ /\ \sigma'_{av})$ = normalized surcharge due to the granular mat; Υ_f = unit weight of the material of granular mat; and h_f = thickness of granular mat. After normalization with σ'_{av},Eq. (2) can be rewritten as

$$q^*_o = q^*_{gpi}\,A_r + q^*_{si}(1 - A_r) \tag{11}$$

Applying the displacement compatibility at the crust-granular pile interface for the ith element within the crust, i.e., $\Delta S_{gpi} = \Delta S_{ci}$, and using Eqs. (7), (8) and (9), following equations are obtained:

If $(\sigma^*_{oi} + q^*_{si}) > \sigma^*_c$, then

$$q^*_{gpi} = R_s\,R_c\ln\left(\frac{\sigma^*_c}{\sigma^*_{oi}}\right) + R_s\ln\left(\frac{\sigma^*_{oi} + q^*_{si}}{\sigma^*_c}\right) \tag{12}$$

and, if $(\sigma^*_{oi} + q^*_{si}) \leq \sigma^*_c$, then

$$q^*_{gpi} = R_s\,R_c\ln\left(1 + \frac{q^*_{si}}{\sigma^*_{oi}}\right) \tag{13}$$

where $R_s = 0.434\frac{C_c}{(1 + e_o)}E^*_{gp}$.

For any element i within the stiff crust, Eqs. (11), (12) and (13) can be solved iteratively to evaluate the value of q^*_{si} and q^*_{gpi} for the applied load q^*_o from which q'_{si}

and q'_{gpi} can be obtained where

$$q'_{si} = \frac{q^*_{si}}{q^*_o} = \frac{q_{si}}{q_o};$$

and $$q'_{gpi} = \frac{q^*_{gpi}}{q^*_o} = \frac{q_{gpi}}{q_o}.$$

Displacement of element, 'i' within the crust can, then, be obtained by using Eqs. (6), (8) and (9).

Formulation for elements within the normally consolidated soft soil remains identical as that given in Shahu et al. (1998). The displacement of a soft soil surrounding the granular pile for element 'i' within the soft soil is obtained as

$$\Delta S_{si} = 0.434 \frac{C_c}{(1 + e_o)} \Delta h_i \ln\left(1 + \frac{q_{si}}{\sigma_{oi}}\right) \tag{14}$$

Satisfying the compatibility condition at the soft soil-granular pile interface for the ith element, i.e., $\Delta S_{gpi} = \Delta S_{si}$, from Eqs. (3) and (14), the following equation may be obtained:

$$q_{gpi} = 0.434 \frac{C_c}{(1 + e_o)} E_{gp} \log\left(1 + \frac{q_{si}}{\sigma_{oi}}\right) \tag{15}$$

After normalization with σ'_{av}, Eq. (15) can be written as

$$q^*_{gpi} = R_s \ln\left(1 + \frac{q^*_{si}}{\sigma^*_{oi}}\right) \tag{16}$$

For any element i within the soft soil, Eqs. (11) and (16) can be solved iteratively to evaluate the value of q^*_{si} and q^*_{gpi} for the applied load q^*_o from which q'_{si} and q'_{gpi} can be obtained. After normalization, Eq. (14) can be rewritten as

$$\frac{\Delta S_{si}}{H} = \frac{1}{C_1} \frac{\Delta h_i}{H} \ln\left(1 + \frac{q^*_{si}}{\sigma^*_{oi}}\right) \tag{17}$$

where $C_1 = \frac{(1 + e_o)}{0.434\ C_c}$. Displacement of ith element within soft soil, ΔS_{si}, can be obtained from Eq. (17).

Evaluation of normalized shear stress, τ'_i, stress concentration factor, $(SCF)_i$, normalized displacement, $\left(\frac{\delta_i}{H}\right)$ and settlement reduction factor, μ remains same for all the elements within the crust and the soft soil, and is obtained in an identical manner as given in Shahu et al. (1998):

$$\tau'_i = \frac{n}{4\,(D_r)} \{q'_{gpi} - q'_{gpi+1}\} \tag{18}$$

Table 1 Nominal value of input parameters

Name of the Parameter	Nominal value
Normalized surcharge due to granular mat, f_s	0.05
Relative stiffness, R_s	20
Area ratio, A_r	0.25
Normalized applied stress, q_o^*	2.00
Number of elements, n	20
Ratio of swell index to compression index, R_c	0.3
Crust thickness, h	0.15
Depth ratio, D_r	10
Soil stiffness factor, C_1	7.68

$$(SCF)_i = \frac{q_{gpi}}{q_{si}} \tag{19}$$

$$\frac{\delta_i}{H} = \sum_i^n \frac{\Delta S_i}{H} \tag{20}$$

$$\mu = \frac{S_t}{S_o} \tag{21}$$

where $D_r = \left(H/d\right)$ = the depth ratio; q'_{gpi+1} = normalized granular pile stress at the center of the element $(i+1)$; S_t = settlement of the granular pile reinforced ground = total normalized displacement for element 1 (δ_1); and S_o = settlement of the untreated ground obtained by using the conventional e-log(p) relationship.

3. RESULTS AND DISCUSSION

Effect of stiff crust on stresses and displacements in the granular pile and soil is evaluated for different crust thicknesses and R_c values. Subsequently, a parametric study is carried out to evaluate the effect of various parameters such as area ratio, A_r, relative stiffness, R_s, normalized surcharge due to granular mat, f_s, etc., on response of the reinforced ground. The nominal values of different parameters used in this study are given in Table 1. To obtain a very smooth normalized shear stress distribution inside the crust, the depth of the soft ground was discretized into 100 elements for plotting τ/q_o versus depth relationship.

Effect of the variation in crust thickness, h_c on normalized granular pile stresses is depicted in Fig. 2. For crust thickness less than or equal to 0.15, normalized granular pile stresses increase with depth inside the stiff crust and decrease with depth within the soft soil. For normalized crust thickness greater than 0.15, normalized granular pile stresses first decrease and then increase with depth inside the stiff crust before merging into a decreasing trend inside the normally consolidated soil zone. Normalized granular pile stresses within the crust decrease with the increasing

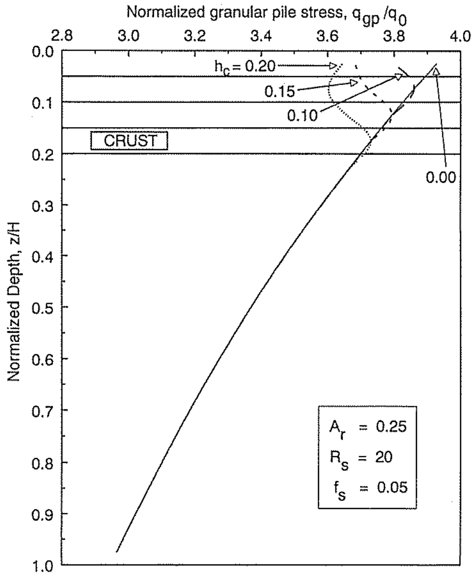

Fig. 2 Effect of Crust thickness on variation of normalized granular pile stress with depth

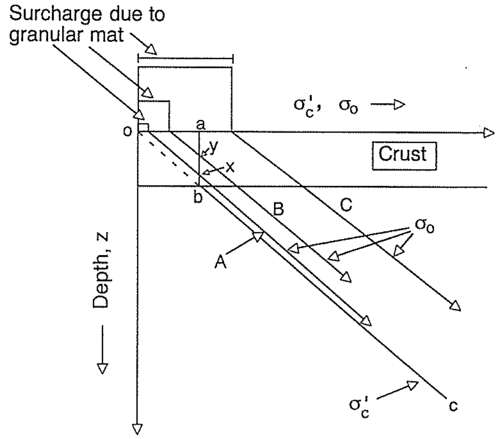

Fig. 3 Modefication of crust stresses due to interaction between crust thickness and fill surcharge

values of h_c. An exactly opposite trend is observed in case of normalized soil stresses. Figure 3 explains the interaction mechanism between crust thickness and the surcharge due to the granular mat that affects the distribution of granular pile and soil stresses inside the hard crust. As shown in this figure, line 'abc' represents the σ_c' versus depth relationship assumed in this analysis. Effective overburden stress, σ_o versus depth relationship will depend upon the surcharge due to the granular mat. The nominal value of f_s assumed for the predictions shown in Fig. 2 ($f_s = 0.05$) corresponds approxi mately to curve B as shown in Fig. 3. Zone 'yb' (y being the point of intersection of line ab and B) behaves as a normally consolidated soil as the total vertical stress for this zone is greater than the maximum past pressure. The extent of zone 'yb' depends upon both the crust thickness and the surcharge due to granular mat. The constitutive relationship for zone 'ay' is given by either Eq. (12) or Eq. (13) depending upon the value of $(\sigma_{oi}^* + q_{si}^*)$ which, in turn, is a function of depth (Eq. 10). Thus, the zone of hard soil crust can be divided into three different subzones each having different constitutive relationship given by either Eq. (12) or Eq. (13) or the soft soil constitutive relationship (Eq. 16) and the same is reflected in Fig. 2.

As the stress concentration factor, *SCF*, is the ratio of granular pile stress to the soil stress, the variation in soil and granular pile stresses is also reflected but in a magnified manner in the *SCF* versus normalized depth relationships shown in Fig. 4, Presence of stiff crust reduces the stress concentration factor significantly and thus, has a beneficial effect on the granular pile reinforced ground. Even a nominal thickness of crust of $h_c = 0.10$ reduces the stress concentration factor at the top from

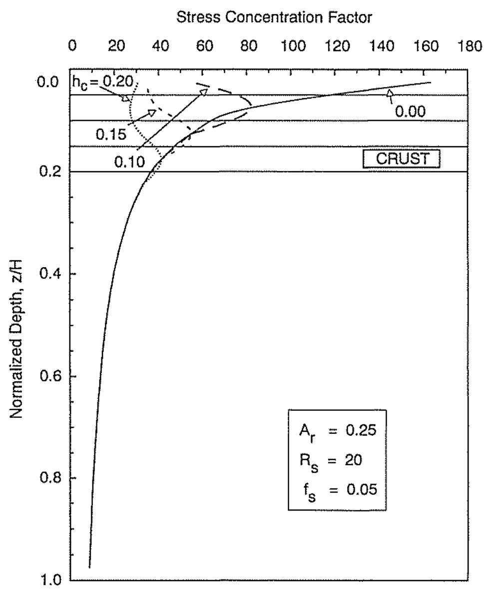

Fig. 4 Effect of Crust thickness on variation of stress concentration factor with depth

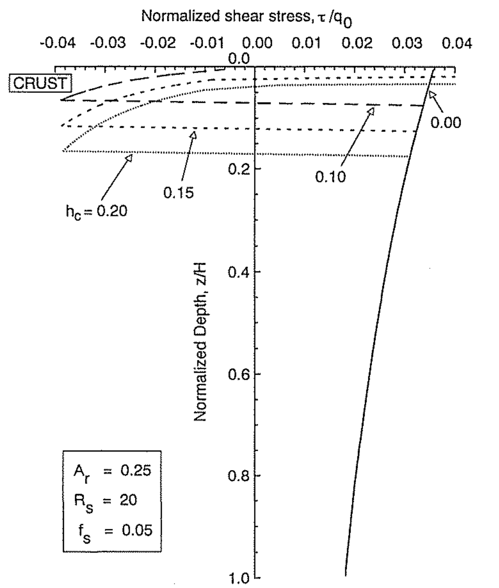

Fig. 5 Effect of Crust thickness on variation of normalized shear stress with depth

164 to 55 (approx by 66 %). A stress discontinuity is observed at the crust-soft soil interface in case of normalized shear stress variation with depth (Fig. 5). Normalized shear stresses decrease continuously with depth inside the stiff crust and become negative. Negative value of normalized shear stress indicates that the granular pile stresses are increasing instead of decreasing, the usual trend (Fig. 2) and the soil s tresses are decreasing instead of increasing at the corresponding depths. It means that at these depths, stresses are transferred from stiff crust to granular pile instead of usual stress transfer from the granular pile to the soil. Thus, the granular pile experiences a downdrag force inside the stiff crust. Crust thickness is found to have no effect on the variation of normalized displacement, δ/H with depth and a continuously decreasing value of normalized displacement with depth (Fig. 6) is observed throughout the reinforced ground.

Figures 6 and 7 compare the variation of normalized total and normalized elemental displacements respectively in untreated soil (with and without crust), the treated ground (again with and without crust) and the granular pile alone acting in isolation. As shown in Fig. 6, crust has very little effect on total normalized displacements at the surface (no effect on treated ground and approx 8% reduction for untreated soil). From Fig. 7, it may be seen that for topmost element, elemental displacement for soft ground without crust is approx 33% greater than the corresponding value for soft ground with crust. In the present analysis, as displacement compatibility is satisfied at each element, curves A or B corresponding to soft soil (Fig. 7) move to curve C (representing elemental displacement of reinforced ground)

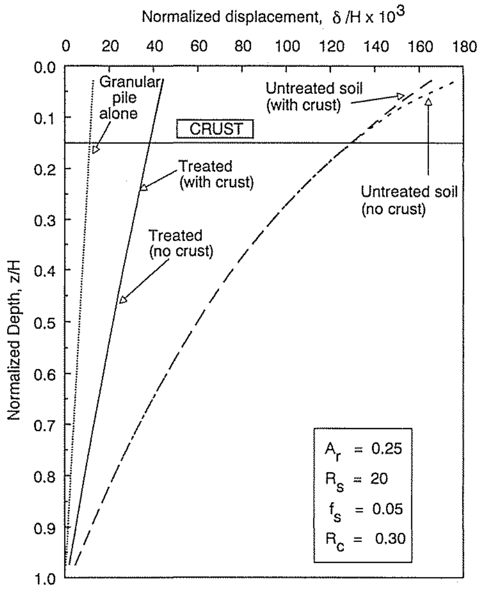

Fig. 6 Effect of Crust thickness on variation of normalized displacement with depth

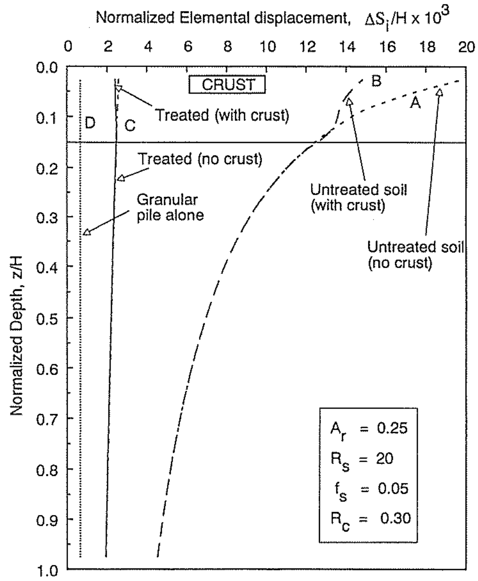

Fig. 7 Effect of Crust thickness on variation of normalized displacement with depth

by reduction in soil stresses whereas curve D (corresponding to granular pile acting in isolation) moves to curve C by increase in granular pile stresses (Fig. 2; h_c = 030) as compared to total applied stresses. Thus, for topmost elements, it is quite evident that a smaller decrease in soil stresses would be required if crust is present and thus, there would be significant reduction in stress concentration factor inside the crust a s depicted in Fig. 4.

Effect of the ratio of swell index to the compression index, R_c on stresses in the crust is shown in Figs. 8 to 10. As the value of R_c increases, normalized granular pile stresses inside the crust also increase (Fig. 8). Increase in R_c leads to less stiff soil in the crust and thus the relative stiffness of the crust zone increases. This increase in relative stiffness, in turn, leads to an increase in the granular pile stresses as shown in Fig. 8. On the other hand, as expected, normalized soil stresses decrease as the value of R_c increases. Figure 9 shows that the increase in R_c value gives rise to a large increase in the stress concentration factor. Thus, it may be seen that more stiff the hard crust is as compared to underlying soft soil, more beneficial will it be in reducing the stress concentration factor. In fact, increase in R_c value from 0.05 to 0.40 increases the stress concentration factor approximately by a factor of 2. Normalized shear stress increases moderately with the increasing value of R_c inside the crust zone as shown in Fig. 10. Downdrag stress (as indicated by the negative value of normalized shear stress) increases continuously with depth inside the crust and achieves a maximum value at a depth of 0.15. This maximum value of downdrag stress on the granular pile increases as the crust becomes more stiffer. R_c is found to have no effect

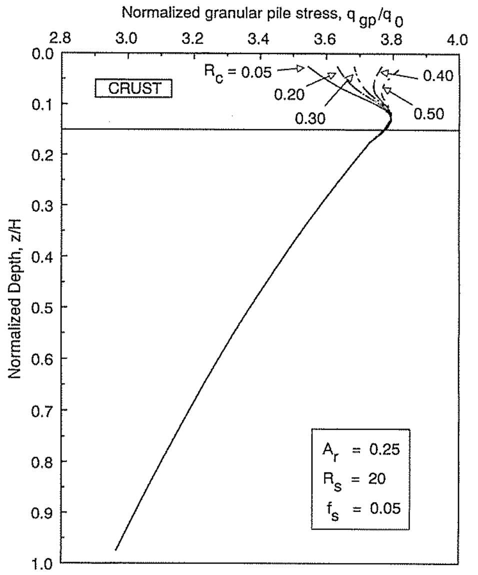

Fig. 8 Effect of R_c on variation of normalized granular pile stress with depth

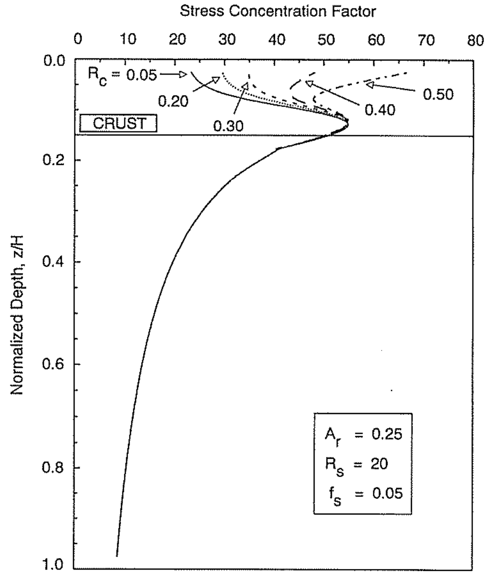

Fig. 9 Effect of R_c on variation of stress concentralion factor with depth

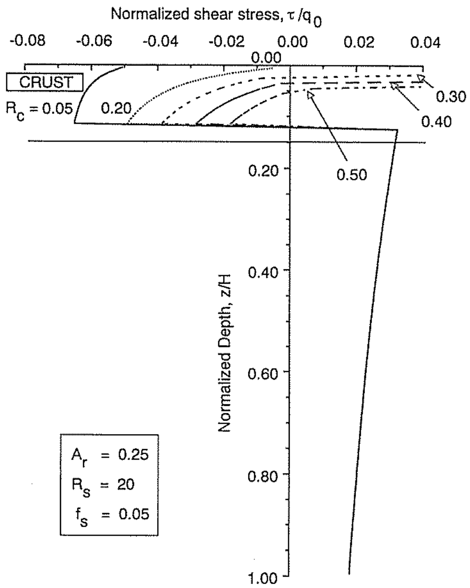

Fig. 10 Effect of R_c on variation of normalized shear stress with depth

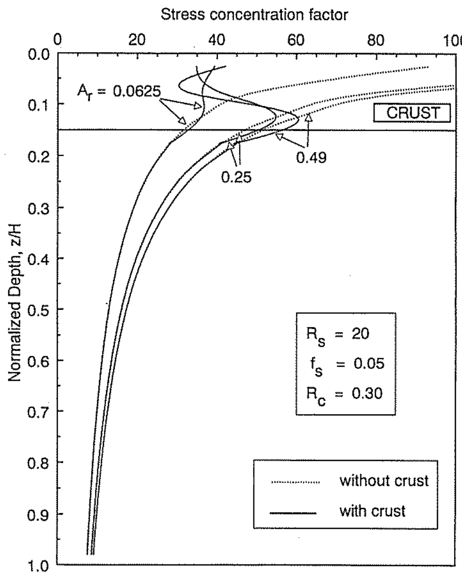

Fig. 11 Effect of Area ratio on variation of stress concentralion factor with depth

on normalized displacement of the reinforced ground.

Increase in area ratio leads to an increase in the stress concentration factor of the treated ground without crust as shown in Fig 11. Presence of crust reduces the stress concentration factor on top of the ground significantly for all area ratios, thus, clearly bringing out the importance of stiff crust in the analysis. Normalized granular pile stresses on top of the reinforced ground reduce due to the presence of crust for all

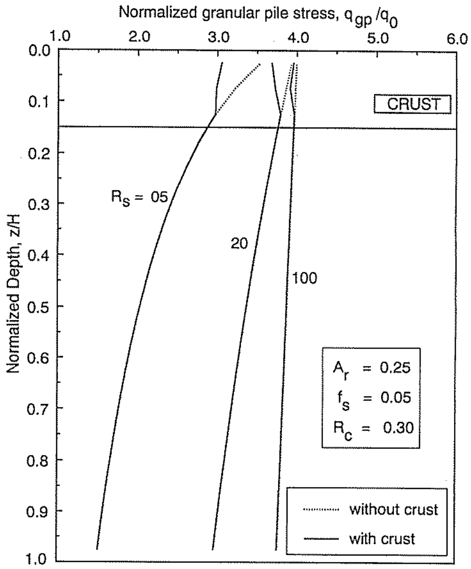

Fig. 12 Effect of relative stiffness on variation of normalized granular pile stress with Effect of depth

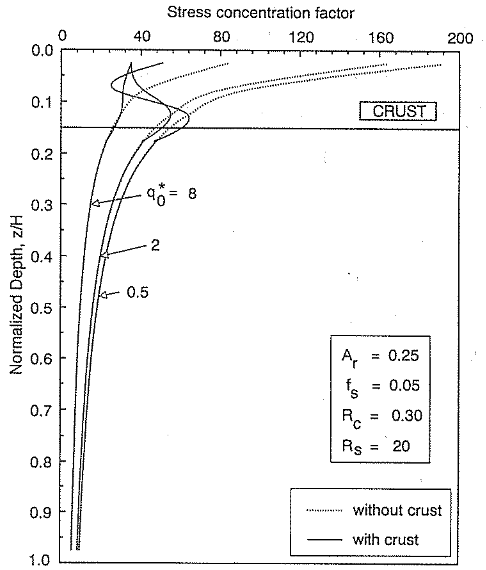

Fig. 13 Effect of applied stress level on variation of stress concentralion factor with depth

values of relative stiffness, R_s (Fig. 12). However, the reduction in granular pile stresses due to the presence of crust is more when the R_s value is low as compared to the case when R_s value is high. Effect of applied stress level on stress concentration factor is shown in Fig. 13. Reduction in stress concentration factor due to the presence of crust on top of the granular pile is found to be more in case of low q_0^* values as compared to higher values of q_0^*.

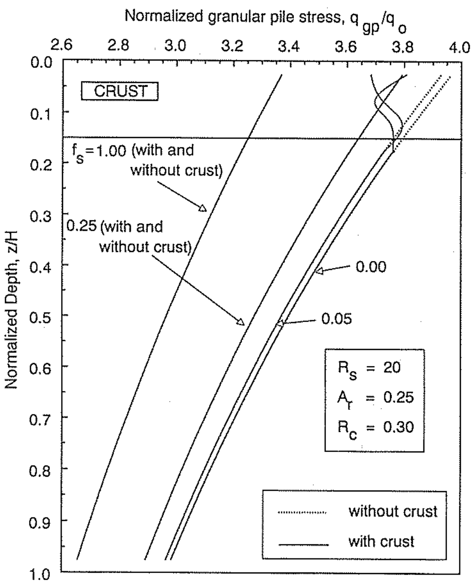

Fig. 14 Effect of granular mat on variation of normalized granular pile stress with depth

Figure 14 shows the effect of granular mat on top of a normally consolidated soil with crust on variation of normalized granular pile stress with depth. In general, normalized soil stresses increase and normalized granular pile stresses decrease with increasing values of f_s in reinforced ground. It may be noted that for $f_s = 0$, normalized granular pile stresses first decrease up to $z/H = 0.075$, then increase up to $z/H = 0.125$ inside the crust and decrease with depth within the soft soil. For $f_s = 0.05$, normalized granular pile stresses increase with depth inside the crust up to $z/H = 0.125$ after which they follow the typical curve for soft soil behaviour. On the other hand, for $f_s \geq 0.25$, normalized granular pile stresses show smooth, decreasing trend with increasing depth both in soft soil and in the crust. Figure 3 once again can be invoked to explain the effect of granular mat on variation in stresses with depth. Curves A, B and C in this figure approximately correspond to the value of $f_s < 0.05$, $f_s = 0.05$ and $f_s \geq 0.25$. Curve C represents the case wherein the stresses due to the granular mat are so large that the total vertical stress, $(\sigma_{oi} + q_{si})$ is always higher than the past maximum pressure and crust behaves like a normally consolidated soil. Curve B($f_s = 0.05$) represents the case for which ($\sigma_{oi} + q_{si}$) for all elements in the zone 'ay' remain greater than σ_c' value and hence for $z/H < 0.125$, stresses are evaluated from only one type of constitutive relationship (Eq. 12). Curve A represents the case wherein for some elements in zone 'ax', ($\sigma_{oi} + q_{si}$) are less than σ_c' and hence for $z/H < 0.125$, stresses are evaluated from two different type of constitutive relationship, top elements by Eq. 13 and others by Eq. 12.

4. CONCLUSION

A simple model for the behaviour of soft normally consolidated soil with stiff crust overlain by granular mat or pad and treated with granular piles is presented. As the crust thickness increases, soil stresses also increase while the granular pile stresses decrease inside the crust zone. As the crust becomes stiffer, soil stresses increase while the granular pile stresses decrease inside the crust zone.

Higher thickness of crust reduces the stress concentration factor significantly and thus, has a beneficial effect on the granular pile treated ground. Stiffer the crust compared to underlying soft soil, more beneficial will it be in reducing the stress concentration factor. Variation of normalized shear stress with depth shows stress discontinuity at the crust-soft soil interface. Downdrag stresses are initialized inside the crust zone for all values of crust thicknesses. The downdrag stresses increase with depth inside the crust and attain a maximum value. The maximum value of this downdrag stress increases as the crust becomes stiffer but remains approximately same for all values of crust thicknesses.

Presence of crust reduces the stress concentration factor significantly for all values of area ratio. It is seen that the reduction in granular pile stresses due to the presence of crust is more for lower values of R_s as compared to the case for higher R_s values. Higher reduction in stress concentration factor for reinforced ground with crust is obtained at smaller applied stress levels as compared to the case of higher applied stress levels. Thickness of granular mat is found to have significant effect on variation of stresses inside the hard crust zone and depending upon the value of f_s, soil and granular pile stresses show three different trends, each representing a different constitutive behaviour. However, the presence of crust would not affect the soil and granular pile stresses in reinforced ground beyond a certain thickness of granular mat.

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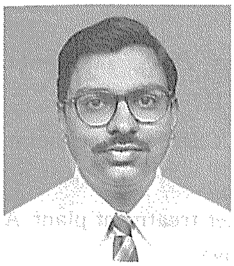

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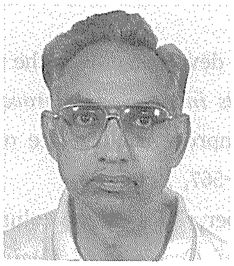

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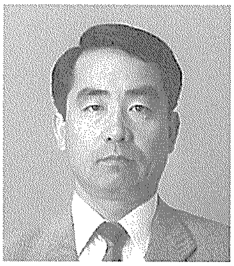

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