Appendix A

The method chosen to analyze the behavior of reinforced two-layer soil bed is similar to the one proposed by Binquet and Lee (1975b) for the analysis of reinforced semi-infinite single layer soil bed. In the following paragraphs the method is discussed in brief. Figure A.1 shows the reinforced semi-infinite soil bed considered in the analysis. Figure A.3(a) illustrates Boussinesq's stress distribution below the strip footing at the level of reinforcement. Assuming Boussinesq's stress distribution beneath the footing to be valid, location of maximum tensile stress in the reinforcement has been defined as shown in the Figure A.3(a). It has been assumed that for an applied load, tensile force in the reinforcement varies inversely with the total number of reinforcements. For strips placed in N horizontal layers, the force or tensile force

\[ T_{D(Z,N)} = \frac{T_{D(Z,N-1)}}{N} \]  

(A.1)

where \( Z \) refers to depth of the reinforcement, \( N \) is the number of layers of reinforcement, \( T_{D(Z,N)} \) is the tension developed at depth \( Z \), for the \( N \)th layer of reinforcement (Figure A.3(b), (c) and (d)).

\( T_{D(Z,N-1)} \) is the required tension in first layer of reinforcement placed at depth \( Z \) to counter the load in excess of bearing capacity of the soil.

Considering static equilibrium of the element of soil influenced by one layer of reinforcement (Figure A.3(b) to (d)).

\[ F_{VAD}(q,Z) - F_{VAD}(q_o,Z) = S(q, Z) - S(q_o, Z) + T_{D(Z,N)} \]  

(A.2)

\[ S(q,Z) = \tau_{xz} (X_o, Z) \Delta H \]  

(A.3)

Defining the shear and normal forces in nondimensional form.
Figure A.1 Reinforced single layer soil bed

- B: Width of the reinforced soil bed
- Footing: Location of the footing
- $u$: Displacement
- $z_1$: Depth of the first layer
- $z_2$: Depth of the second layer
- $E_2/E_1 = 1$: Ratio of the moduli of the two layers
- $\Delta H$: Difference in height between the two layers
- Reinforcements: Placement of reinforcement materials
\[ F_{\text{vad}}(q,Z) = J(Z/B)qB \]  

(A.4)

\[ J(Z/B) = \int_{0}^{Z/B} \frac{\sigma_{z}(Z/B)dx}{qB} \]  

(Figure A.3(e))  

(A.5)

\( X_0 \) is the distance from the centre of footing where \( \tau_{xz} \) is maximum (Figure A.3(e))

\[ S(q,Z) = I(Z/B)\Delta H \]  

(A.6)

\[ I(Z/B) = \frac{\tau_{xz,\text{max}}(Z/B)}{q} \]  

(A.7)

and  

\[ T_{D} \text{ or } T_{D(Z,N)} = \frac{1}{N} \left[ J(Z/B) - B - I(Z/B)\Delta(Z/q)_{0} \right] - 1 \]

The integrated values of \( J/Z/B \) or \( J \) and \( I/Z/B \) or \( I \) have been presented in Figure A.2(a) as a function of \( (Z/B) \). In the above formulations \( \sigma_{z}(Z/B) \) and \( \tau_{xz}(Z/B) \) refer to the normal vertical and shear stresses at \( Z \) below the footing of width \( B \).

Reinforcement pullout resistance is a function of normal pressure acting over the length \( (L_{o} - X_{o}) \), where length \( L_{o} \) correspond to the point at which vertical stress is 1% of applied pressure on the footing. The normalised length parameters \( L_{o} \) and \( X_{o} \) are given in Figure A.2(b). If \( w \) is the width of the strip reinforcement per unit length of the strip footing, total vertical normal stress is \( F_{N} \), which is as follows:

\[ F_{N} = F_{\text{vad}}(q,Z) + LDR \gamma w (L_{o} - X_{o})(Z + D_{f}) \]  

(A.9)

where \( LDR \) is the linear density ratio of the reinforcement,

\( \gamma \) is density of the soil,

\( w \) is the width of the strip reinforcement,

\( D_{f} \) is the depth of the footing.

\[ F_{\text{vad}}(q,Z) = LDR B M(Z/B) \]  

(A.10)
Figure A.2(a) Nondimensional force parameters

Figure A.2(b) Nondimensional length parameters
(after Binquet and Lee (1975b))
and $M(Z/B)$ or $M = \int_{x_0}^{x} \sigma z (Z/B)dx$ (Figure A.3(d)) (A.11)

For unit length of the strip footing, frictional pullout force for reinforcement or pullout resistance of reinforcement, $T_f$ at depth $Z$, is given by

$$T_f(z) = 2f L D R M B q_c (\frac{q}{q_0}) + \gamma (L_o - X_o) (Z + D_f)$$  (A.12)

in which, $f$ is the soil reinforcement coefficient ($f = \tan \phi_u/F_{sf}$; $\phi_u$ is the angle of internal friction between soil and reinforcement, $F_{sf}$ is the factor of safety against friction), $D_f$ is the surcharge load of soil of depth above the base of the footing.

Tensile resistance of the reinforcement is given by

$$R_y = \frac{w N_R F_y t}{F_{sy}}$$  (A.13)

in which, $R_y$ is the tensile resistance of reinforcement, $N_R$ is the number of reinforcing strips for layer of reinforcement, $F_y$ is the breaking strength of reinforcement and $F_{sy}$ is the factor safety against breaking strength.

Load carrying capacity calculations require evaluation of all these three parameters viz., $T_D$, $R_y$ and $T_f$ given by equations (A.8, A.13 and A.13). Comparison of two allowable resisting forces $R_y$ and $T_f$ with tensile force $T_D$ will define the mode of failure and maximum load the system can sustain. LCR of each layer is given by the minimum of LCR's, $LCR_f$ and $LCR_t$. LCR of the system is the minimum LCR of the layers.
No reinforcing
(b) Soil only

With reinforcing
(c) Soil component  (d) Tie component

Strip footing 1 unit long

Figure A.3 - Method of Analysis on mechanism of failure
Appendix B

DESCRIPTION OF THE FLOW CHART OF NLSRIP

A flow chart of NLSRIP is given in Figure B.1. Brief description of the NLSRIP and functions of the subroutines are as specified below:

Subroutine INPUTNP reads and prints nodal point data, and sets equation number according to the boundary conditions.

Subroutine BAR or BEAM reads and prints reinforcement element data and calculates the internal force-displacement matrix.

Subroutine CALBAN calculates the band width of group of elements.

Subroutine LAYOUT reads and prints the soil and interface input data and compute initial stresses.

Subroutines ELAW and IELAW calculate modulii values for soil and interface elements respectively in accordance with magnitude of stresses.

Subroutines FORMST and DERIVE establish strain-displacement matrix for soil elements.

Subroutine IDERIVE establish strain-displacement matrix for interface elements.

Subroutine CALBLK determines the number of elements and nodal points for the entire mesh and sets up equations.

Subroutine FVECT calculates nodal point forces and sets up force vector.

Subroutine POREF reads element incremental pore water pressures and computes equivalent nodal forces.

Subroutines ISQUAD and IISQUAD formulate the constitutive equations for soil and interface elements respectively.

Subroutine ADDSTF calculates total stiffness matrix for each increment by adding appropriate element stiffness coefficients.

Subroutine SYMBAN solves the simultaneous equations representing the stiffness matrix and the load vector for nodal point displacements, using Gaussian elimination technique.

Subroutine ISRSLT calculates incremental stresses and modules after first iteration (IT=1), and calculates cumulative stresses in the second iteration (IT=2).

Subroutines MOD, A1 and TAPER calculate the displacement and force matrix for reinforcement element.
Figure B.1 Flow Chart of NLSRIP
Appendix C

LIST OF PUBLICATIONS BY THE AUTHOR
