CHAPTER 7
SUMMARY AND CONCLUSIONS

7.1 SUMMARY

In recent years the concept of reinforced earth technique has been considered as
one of the important construction techniques in the field of civil engineering. The rapid
acceptance of reinforced earth by civil engineering profession, which is generally
regarded as very conservative, has been remarkable. There are several forms of earth
structures which have been built economically adapting this technique as an alternative to
conventional earth structures such as embankments, retaining walls and bridge
abutments. Reinforced soil beds have been adopted for highway pavements and railway
sub grades to increase the bearing capacity and reduce the settlements. However, though
it is well established fact that reinforcing soil technique can be utilized to improve the
load carrying capacity of weak soil foundations, no major structures have been built till
today using the technique of reinforced soil foundations. One of the important reasons
could be due to lack of reliable method of analysis and design. This only shows that
much remains to be done by the way of analysis and design before this technique can
gain more legitimate and wider acceptance in practice.

Several researchers (Basset and last, (1978); Singh, (1988); Madhav and
Pitchumani, (1991); Balakrishna, (1992); Beena, (1993); Waugh and Chandrasekharan,
(1995); Raghavendra et al., (1995 and 1997); Nainan et al., (1997); Raghuveer Rao et al.,
(2000); Kentaro Yamamoto and Jun Otoni, (2001); Shin et al., (2001); Raghavendra,
(2004)) in literature have conducted analysis on the surface/embedded footings carrying
the horizontal reinforcement in the soil bed and show that factors such as non-linear
confining stress development behaviour of soil, properties of soil and reinforcement and
configuration of reinforcement have marked influence on the behaviour of reinforced soil
beds. It is quite clear that it is difficult and time consuming to conduct experimental or
model studies to understand the influence of each of these parameters on the behaviour of
reinforced soil beds either independently or jointly. Moreover, incorporating the
influence of all these parameters into any closed form solutions is also difficult.

Due to inherent difficulties to carry out a prototype test of reinforced soil beds,
still the model tests are the only practical means by which one can study the behaviour of
reinforced soil beds. Hence it is very important to characterize the conditions prevailing
in model test as accurately as possible so that the analysis and design method developed
using model tests can be used with confidence for the design of reinforced soil beds or
foundations therefore to completely understand the behaviour of reinforced soil beds numerical techniques such as finite element analysis are more advantageous as they can take into account all the factors which influence the behaviour of reinforced soil beds. Studies on reinforced soil bed strengthened by vertical or inclined pattern (practical pattern of reinforcement) is very rarely available in literature. Hence an attempt is made here to study the effect of vertical/inclined reinforcement below the surface/embedded footing under static load using rigorous non linear finite element analysis.

In many practical situations soil beds are often non-homogeneous and layered in nature, exhibiting varying strength characteristics. It is quite common to find a finite stiffer layer of soil overlying a soft lower layer. Reinforcements are often included in such two-layer soil beds in the upper granular fill to improve the load carrying capacity of the system. Hitherto, very limited studies are available on reinforced two-layer soil beds (Giround and Noiray, 1981; Bindumadhava, 1990 and Brocklehurst, 1993). Even reported research works in case of analysis of reinforced two-layer soil beds are limited to pavements where the emphasis is on repeated loading. Hence there is a need for research work to analyze the behaviour of footing resting on reinforced two-layer soil beds subjected to incremental loading. Raghavendra (1996) has conducted analysis on the two layer soil bed carrying the horizontal reinforcement. However, studies on reinforced two layer soil bed strengthened by inclusion of vertical/inclined reinforcement pattern (practical pattern of reinforcement) is very rarely available in literature. Hence an attempt is made to study the effect of vertical/inclined reinforcement in two layer soil bed under static load using rigorous non linear finite element analysis.

In the light of the above discussions this study has been essentially aimed at characterising the behaviour of reinforced soil bed (both as homogenous and two-layer soil beds) by developing a rigorous non-linear finite element analysis for reinforced soil bed. This provides a better insight into soil-reinforcement interaction mechanism and clear understanding overall behaviour.

The behaviour of reinforced soil beds (both as homogenous layer soil bed and two-layer soil bed) at each increment of imposed footing load is observed, step by step and element by element, using NLSRIP by studying altered stresses, displacements and failure patterns inside the soil bed due to the inclusion of reinforcements. From the details of the results it is found that the behaviour of reinforced soil bed can be fully and effectively predicted using present finite element formulation and over all behaviour of the reinforced soil beds can be explained.
7.2 CONCLUSIONS

The conclusions drawn from this work are presented in the following three parts.

7.2.1 Behaviour of Reinforced soil bed with vertical / inclined reinforcements as a homogenous (single layer) soil bed beneath surface footing.

- The introduction of the reinforcement increases the load carrying capacity and decreases the settlement of soil bed for any given load.

- As the number of layers of reinforcement increases load carrying capacity increases up to certain limit. In the present study optimum number of layers of reinforcement is found to be three layers with spacing 0.25B and embedment depth of reinforcement 0.0B.

- Load carrying capacity increases with imposed footing load and reinforcement is better utilized at higher loads.

- For soil bed with vertical reinforcements optimum length of reinforcement is 3B.

- For soil bed with inclined reinforcements optimum length of first layer is 0.707B, second layer's is 1.060B, third layer's is 1.414B and angle of inclination of reinforcement is 45°.

- Principal stresses are higher beneath and near footing. Higher stresses beneath the footing for reinforced soil beds point to the fact that there is frictional interaction between soil and reinforcement.

- Nodal displacement vectors and deformed meshes show that the inclusion of reinforcement resulted in reduction of settlement beneath the footing and reduced heave of the soil mass by the side of footing.

- Location of failed elements suggests that the failure commences from the edge of the footing at soil footing interface. The depth of this soil wedge is more for reinforced soil beds indicating that soil beneath the footing in reinforcement zone behaves like a part of the footing.

- Principal stresses are greater, magnitude of displacements are lesser, deformation and number of failure elements are also less in the analysis using soil bed with inclined reinforcements when compared to the analysis using soil bed with vertical reinforcements.
7.2.2 Behavior of Reinforced soil bed with vertical / inclined reinforcements as a homogenous (single layer) soil bed beneath embedded footing.

- Principal stresses are greater, magnitude of displacements are lesser, deformation and number of failure elements are also less in the analysis using soil bed beneath embedded footing when compared to the analysis using soil bed beneath surface footing.
- Other parameters are similar to the soil bed beneath surface footing.

7.2.3 Behavior of Reinforced soil bed with vertical / inclined reinforcements as a two-layer soil bed.

- Load carrying capacity of two-layer soil bed increases with increase in depth of fill.
- Load carrying capacity of two-layer soil bed with fill thickness $H=B$, is found to be very close to the granular soil bed alone (single layer)
- For fill depth $H=B$, the behaviour of two-layer reinforced soil bed is similar to the single layer (granular fill) reinforced soil bed in terms of the analysis of principal stresses and their directions, nodal displacement vectors and their trajectories, deformed meshes, failure initiation progression and the stresses and stress contours.

7.3. SCOPE FOR FURTHER RESEARCH WORK

The investigations reported in the thesis are aimed at developing methods for analysis of reinforced soil beds for foundations and by no means exhaustive. Further research on the following aspects merits exploration.

i) The finite element formulation reported in this thesis can be extended for different shapes of footings.

ii) The representation of reinforcing elements can be improved by adding required additional degree of freedoms to take care of behaviour of highly flexible reinforcements.

iii) The present finite element formulation can be extended to three dimensional analysis of reinforced soil beds.