CHAPTER 7
SUMMARY OF CONCLUSIONS

7.1 Introduction

An extensive field testing was performed to study the behavior of expansive clay beds reinforced with granular pile-anchors in situ. The testing programme was focused on studying the efficacy of the innovative granular pile-anchor foundation (GPAAF) system in minimizing heave of foundations laid in expansive clay beds in situ and in improving their engineering behavior. The test programme included the study of ground improvement aspect, compressive load response and the pullout load response of the expansive clay beds reinforced with granular pile-anchors in situ. The conclusions drawn from the different aspects of the study in this thesis may be summarized as follows:

1.2 Ground improvement aspect

Installation of granular pile-anchors in expansive clay beds in situ reduced the amount of heave effectively. Of the various combinations of length (l_{ap}) and diameter
of the granular pile-anchors, a maximum of 90% reduction in heave was observed, when the length of the pile-anchor ($l_{gp}$) was 1000 mm and the diameter ($d_{gp}$) was 200 mm. It was observed that, for a given surface area of granular pile-anchor, increasing pile-anchor diameter ($d_{gp}$) was more effective in the reduction of heave than increasing pile-anchor length ($l_{gp}$).

2. Reduction in heave of expansive clay beds due to installation of granular pile-anchors could be attributed to the weight of the granular pile-anchor acting in the downward direction, the effect of anchorage which made the granular pile-anchor tension-resistant and the frictional resistance mobilized along the pile-soil interface to resist the uplift force caused on the foundations.

3. The amount of heave of the expansive clay beds reinforced with granular pile-anchors varied with radial distance from the center of the granular pile-anchor. While it was negligible at the center of the granular pile-anchor, it increased with increasing radial distance from the center of the granular pile-anchor, reaching a value of 10.5% at a radial distance of 750 mm or 5d from the center of the granular pile-anchor.

4. Unconfined compressive strength (UCS) of the expansive clay beds reinforced with granular pile-anchors increased with respect to that of un-reinforced expansive clay beds. UCS increased with depth in both reinforced and un-reinforced clay beds. At any depth of the clay bed, the granular pile-anchor-reinforced clay bed showed increase in UCS indicating that the ambient expansive clay improved in the engineering behavior on being reinforced with granular pile-anchor.

5. Proctor needle penetration tests conducted on un-reinforced expansive clay beds and clay beds reinforced with granular pile-anchors indicated that the reinforced clay
beds offered greater amount of penetration resistance than the un-reinforced clay beds. For example, the penetration resistance offered by the un-reinforced expansive clay bed at mid-depth was 125 N, whereas that offered at mid-depth by the clay beds reinforced with granular pile-anchors was respectively 165, 185 and 215 N when pile-anchors of length 1000 mm and diameters 100, 150 and 200 mm were installed.

**7.3 Compressive load response**

1. The expansive clay bed reinforced with granular pile-anchor (composite ground) gave an improved compressive load response in comparison to the un-reinforced clay bed. The stress required to cause a settlement of 25 mm in the case of composite ground was 500 kN/m² as against 200 kN/m² in the case of un-reinforced expansive clay bed, showing an improvement in the load-carrying capacity of 150%.

2. The compressive load response of granular pile-anchor alone further improved. When the granular pile-anchor alone was loaded, the applied load was resisted by compacted granular material alone. The stress required to cause a settlement of 25 mm in the case of granular pile-anchor alone was 675 kN/m², indicating a percentage improvement of 240% in load-carrying capacity with reference to un-reinforced expansive clay bed.

3. The compressive load response of the expansive clay bed reinforced with a group of granular pile-anchors also showed a significant improvement in load-carrying capacity over the un-reinforced clay bed. As the decrease in dry unit weight or the increase in the void ratio of the clay bed owing to heaving of clay was arrested by granular pile-anchors, the compressive load response was better than the un-reinforced clay bed. A percentage
improvement of 65 was observed in load-carrying capacity in the case of the clay bed reinforced with 3-group granular pile-anchors over the un-reinforced expansive clay bed.

4. The maximum bulge diameter increased with increasing diameter and length of the pile-anchor. The maximum bulge diameter increased from $1.27d_{ga}$ to $1.42d_{ga}$ when length of pile-anchor increased from 500 to 1000 mm. Similarly, the maximum bulge diameter increased from $1.3d_{ga}$ to $1.42d_{ga}$ when the diameter of the pile-anchor increased from 100 mm to 200mm. The effect of diameter of granular pile-anchor was more on bulge diameter than that of length of granular pile-anchor.

5. The maximum bulge length increased with increasing diameter and length of granular pile-anchor. The effect of length of granular pile-anchor is more pronounced on increase in maximum bulge length than that of diameter. The percentage increase maximum bulge length was 29% in granular pile-anchor of 1000 mm when the diameter increased from 100 to 200 mm, whereas the percentage increase in maximum bulge length was 37% in a granular pile-anchor of 100 mm diameter when its length was increased to 500 to 1000 mm.

7.4 Pullout load response

1. The upward load required to be applied on the granular pile-anchor to cause a given upward movement increased with increasing length of granular pile-anchor. For granular pile-anchors (GPA) of length 500, 750 and 1000 mm, the uplift load required to cause an upward movement of 25 mm in the granular pile-anchor was respectively 9, 12 and 14 kN. When the length of the GPA was increased from 500 mm to 750 mm and
1000 mm, the percentage increase in the uplift load required for an upward movement of 25 mm was 33.3% and 55.5% respectively.

2. The uplift load or failure pullout load increased with the increasing diameter of the granular pile-anchor also. This is because the resistance to uplift increased with increasing surface area of the pile-soil interface consequent upon increase in the diameter. The uplift load required to be applied on the granular pile-anchor (1000 mm) for an upward movement of 25 mm was respectively 11, 11.5 and 14.2 kN for granular pile-anchors (GPA) of diameter 100, 150 and 200 mm. This indicates that the percentage increase in the uplift load required for an upward movement of 25 mm was 5% and 30% when the diameter of the GPA was increased from 100 mm to 150 mm and 200 mm.

3. For a given $l_{gp}/d_{gp}$ ratio the failure pullout load increased with increasing length of the granular pile-anchor. The failure pullout load for granular pile-anchors (GPA) of $l_{gp}/d_{gp}$ ratio of 5 was respectively 5, 11 and 15 kN, when length of granular pile-anchor changed as 500, 750 and 1000 mm. Similarly, for a given length of the granular pile-anchor (GPA), the failure pullout load increased with decreasing $l_{gp}/d_{gp}$ ratio. Increasing diameter increases the surface area and consequently the uplift resistance and results in increased failure pullout load. The failure pullout load of granular pile-anchor of length 1000 mm was 11, 13 and 15 kN where the $l_{gp}/d_{gp}$ ratio was 10, 6.67 and 5 respectively (for diameters 100, 150 and 200 mm).

4. The uplift load (kN) required to be applied for any given upward movement (mm) of the field scale granular pile-anchor (GPA) was significantly higher than that in the case of laboratory scale granular pile-anchor. This was irrespective of the $l_{gp}/d_{gp}$ ratio. For
example, the failure pullout load of field scale granular pile-anchor was 10 kN as against 0.90 kN in the case of laboratory scale granular pile-anchor for the same \( l_p/d_p \) ratio of 10. The uplift load required to cause an upward movement of 25 mm in the case of laboratory scale GPA was equal to 0.35 kN, whereas, in the case of field scale granular pile-anchor, the uplift load required for the same amount of upward movement of 25 mm was 11 kN.

5. The theoretically predicted ultimate resistance to pullout of the GPA tallied very closely with in situ failure pullout load in most of the cases. The percentage variation was between -23.4 to +42.6. This is within tolerable limits.

6. The granular pile-anchor under group effect resulted in increased uplift load for a given upward movement in comparison to that of the granular pile-anchor when tested single. The uplift load required to be applied on the granular pile-anchor to cause an upward movement of 25 mm was 13.7 kN when tested under group effect as against an uplift load of 11.25 kN for the same amount of upward movement of 25 mm when tested single. The failure pullout load of the granular pile-anchor when tested under group was 18 kN as against a failure pullout load of 12 kN for the granular pile-anchor when tested single, indicating an improvement of 50% in the failure pullout load.
REFERENCES


I.S : 2720, Part 13, 1972 - Determination of Shear parameters by Direct Shear

I.S : 2720, 1974 - Determination of Compaction Characteristics by Proctor Compaction.


