Chapter 8

Pullout behaviour of GPAs subjected to varied swelling and shrinkage

8.1 INTRODUCTION

The uplift behaviour of the GPAs embedded in expansive clay beds is a function of uplift force \( (P_u) \) and resisting force \( (P_R) \), which depend on the degree of swelling and shrinkage. Hence, it is required to study the pullout behaviour of GPAs under the effect of swelling and shrinkage. Pullout load is an important design parameter in the case of GPAs. The variation in water content, \( c' \) and \( \phi' \) during different stages of swelling and shrinkage significantly affect the pullout behaviour of GPAs. This chapter presents experimental data obtained from two series of pullout tests conducted on laboratory scale GPAs embedded in expansive clay beds subjected to varying swelling and shrinkage. In the first series of pullout tests, varying amounts of water (cc) were allowed into the clay beds to cause varying degrees of swelling. In the second series of pullout tests, fully inundated GPA-reinforced expansive clay beds were subjected to varying periods of shrinkage. Pullout tests were conducted at the end of swelling and shrinkage. Useful data were obtained. Pullout tests were conducted in two different series as described in Chapter 3. Section 3.4.2 describes the pullout tests. The first series of tests studies the influence of varying swelling and the second series studies the influence of varying shrinkage on pullout behaviour of GPAs. The following sections discuss the test results obtained.

8.2. TEST SERIES I: INFLUENCE OF DEGREE OF SWELLING

Figure 8.1 shows the rate of heave of GPA-reinforced clay beds into which different amounts of water were allowed so that the water contents of the clay beds were \( w = 10\%, 20\%, 30\%, 40\%, 50\%, 60\% \) and \( 70\% \). Heave increased with increasing water content of the clay beds. The equilibrium heave attained by the clay beds was 27mm, 35.4mm, 47.8mm, 52mm, 53.5mm, 54mm and 55mm respectively for the water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%. As all the clay beds were identical in the
as-compacted condition (w = 0%), the heave profiles of the clay beds were close to one another. But, the equilibrium heave increased with increase in water content as shown in Figure 8.2. The data in Figure 8.2 show that, at higher water contents (above w = 40%), the equilibrium heave was, more or less, stabilized. This shows that, at water contents above 40%, the degrees of saturation of the clay beds were high. The degrees of saturation obtained were 20%, 37%, 51%, 67%, 82%, 98% and 100% respectively for water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%. Figure 8.2 also shows the variation of degree of saturation with water content (w%). The degree of saturation and equilibrium heave at given water content of the clay bed can be read from Figure 8.2.

![Fig 8.1. Rate of heave for different water contents](image-url)
Figure 8.3 shows the pullout behaviour of GPAs embedded in clay beds having test water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%. The data are plotted in the form of uplift load ($P_u$) – upward movement ($\delta$) curves. The clay bed at a water content of 70% indicated 100% degree of saturation. Hence, the corresponding $P_u$-\(\delta\) curve indicated failure. The end portion of the curve, tending to be asymptotical with ‘x’ axis at an applied pullout load of 225N, indicated failure. The $P_u$-\(\delta\) curves of GPAs tested at lower water contents indicate that the pullout behaviour of the GPAs improved as the test water content decreased. Frictional resistance to uplift, generated on the cylindrical GPA-clay interface, increases with decreasing water content. It is a function of shear parameters $c'$ and $\varphi'$ of the GPA-clay interface. As GPAs move in the upward direction under the applied pullout load, shear resistance is mobilized along the GPA-clay interface. The interface shear parameters $c'$ and $\varphi'$ were determined by conducting shear box tests corresponding to the test relative density ($D_r$) of the GPA material and the test water content (w %) of the expansive clay (see Section 3.4.2.4).

Figure 8.4 shows the failure planes obtained for different GPA-clay interfaces corresponding to different test water contents. $c'$ increased and $\varphi'$ decreased with increasing water content. The uplift load ($P_u$) required to be applied on a given GPA for a
given upward movement ($\delta$) was thus governed by the corresponding $c'$ and $\phi'$. Figure 8.5 shows the variation of uplift load $P_u$ with $c'$ and $\phi'$ for a given upward movement ($\delta$) of 0.5 mm. $P_u$ increased with increasing $\phi'$, and decreased with increasing $c'$. Previous research on pullout behaviour of GPAs (Phanikumar, 1997; Phanikumar et al. 2004) also yielded similar results. Further, $P_u$ for a given $\delta$ increased with decreasing water content. For example, the upward load ($P_u$) required to be applied on the GPAs for a given upward movement ($\delta$) of 0.5 mm was respectively 240N, 215N, 185N, 170N, 145N, 130N and 120N for test water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%. Figure 8.6 shows the variation of pullout load ($P_u$) with water content (w%). The data pertain to an upward movement of 0.5 mm.

![Fig 8.3. Pullout behaviour of GPAs under varying water content (w%)](image-url)
Fig 8.4. Failure planes

Fig 8.5. Variation of $P_u$ (N) with cohesion (c) and friction angle ($\phi$) - upward movement ($\delta$) of 0.5mm
8.3. TEST SERIES II: INFLUENCE OF DEGREE OF SHRINKAGE

Figure 8.7 shows the heave (mm) - log time (minutes) plots for unreinforced clay beds (n = 0) and clay bed reinforced with a single (n = 1) granular pile anchor (GPA). Heave was allowed for 10 days in both the cases. Heave increased with increase in time in both the clay beds (n = 0 and n = 1). The data show that heave of GPA-reinforced clay bed (n = 1) was less than that of the unreinforced clay bed (n = 0). When an expansive clay bed is reinforced with a GPA, a tension-resistant foundation technique, heave is controlled because tensile uplift force on the GPA, caused due to swelling of the expansive clay, is resisted effectively by the shear resistance mobilized in the downward direction along the GPA – clay interface.

The amount of heave recorded in the case of unreinforced clay bed (n = 0) and GPA-reinforced clay bed (n = 1) were respectively 56.6 mm and 46 mm. The fully swollen GPA-reinforced expansive clay beds (n = 1) were allowed, by evaporation of water, to shrink through different time periods of 15 days, 30 days and 45 days.
Figure 8.8 shows the rate of shrinkage (vertical shrinkage in contrast to vertical heave shown in Figure 8.1) of identical GPA-reinforced expansive clay beds (n = 1) for time periods of 15 days, 30 days and 45 days. The figure also shows shrinkage data of the unreinforced expansive clay bed (n = 0) for 45 days. Shrinkage (mm) increased with increasing time period in both the clay beds (n = 0) and (n = 1). As the amount of water that evaporates from the clay bed increases with increasing shrinkage period, shrinkage (mm) increases with increase in shrinkage period (days). Shrinkage (mm) recorded in the case of un-reinforced clay bed (n = 0) for 15 days, 30 days and 45 days was higher than that recorded in the case of GPA-reinforced expansive clay beds (n = 1). The data indicate that shrinkage was also effectively controlled in the case of GPA-reinforced expansive clay beds. This can also be attributed to the frictional resistance to the downward movement during shrinkage. The shrinkage (mm) recorded in unreinforced clay bed (n = 0) was 18.7mm for a shrinkage period of 45 days, whereas the shrinkage recorded in GPA-reinforced expansive clay bed was equal to 7.8mm, 3.76mm and 1.58mm respectively for shrinkage periods of 45 days, 30 days and 15 days. This establishes the efficacy of GPA reinforcement in controlling shrinkage also. Figure 8.9 shows, by comparison, the variation of shrinkage (mm) with time period in unreinforced
expansive clay bed ($n = 0$) and GPA-reinforced expansive clay bed ($n = 1$). When shrinkage period increased from 15 to 45 days, shrinkage (mm) increased from 4mm to 18.7mm in unreinforced expansive clay bed, and from 1.58 mm to 7.8 mm in GPA-reinforced expansive clay bed. The data depict the way shrinkage is controlled by GPA technique.

![Fig 8.8. Rate of shrinkage](image-url)
Figure 8.10 shows the pullout behaviour of GPAs subjected to different shrinkage periods (0, 15, 30 and 45 days). The data reflect the influence of shrinkage period on $P_u$ (N)–$\delta$ (mm) behaviour of GPAs. The data indicate that $P_u$–$\delta$ behaviour improved with increasing shrinkage period. $P_u$–$\delta$ curve for GPA at 0-day shrinkage period indicates failure, the final portion of the curve being asymptotical with the X-axis. The $P_u$–$\delta$ curves of GPAs at longer shrinkage periods shifted upwards. The uplift load ($P_u$) required to be applied on a GPA for a given upward movement ($\delta$) increased with increasing shrinkage period. For example, the uplift loads ($P_u$) on GPAs subjected to shrinkage for 0, 15, 30 and 45 days were respectively 100N, 110N, 140N and 270N for an upward movement ($\delta$) of 2.5 mm. As water evaporates from the clay bed, the frictional resistance ($P_R$) to the uplift load ($P_u$) increases. Hence frictional resistance ($P_R$) increases with increasing shrinkage period. Frictional properties of the GPA-clay interface get modified with increasing shrinkage period, resulting in higher value of $P_u$ for a given deformation ($\delta$). As vertical shrinkage (mm) also increases with increasing shrinkage period, it can be correlated with $P_u$. Figure 8.11 shows the variation of $P_u$ (for $\delta = 2.5$ mm) with shrinkage period (days) and amount of shrinkage (mm).
Fig 8.10. Pullout behaviour of GPAs under varying shrinkage

Fig 8.11. Variation of uplift load ($P_u$) with shrinkage period (days) and shrinkage (mm)
After conducting the pullout tests on GPAs for different shrinkage periods, clay samples were collected from the test beds for the determination of water contents. Samples were collected at different depths of clay bed (0 mm, 100 mm and 200 mm). Figure 8.12 shows the water content profiles for different shrinkage periods. Water content decreased at all depths with increase in shrinkage period. The variation in water content at the top of the clay bed was large, but it decreased with increasing depth from the top of the clay bed. This is according to the previous research on water content and suction at different depths of expansive soils (see Chen, 1988). The change in water content at the top of the clay bed was 47 % and was 16 % at the bottom of the clay bed.

As water evaporated from the clay beds subjected to different shrinkage periods, the clay beds developed polygonal shrinkage cracks. Crack width increased with increase in shrinkage period. Figure 8.13 shows the variation of crack width with increasing shrinkage period. The widest crack measured was 7 mm for the shrinkage period of 45 days. Figure 8.14 shows the variation of pullout load ($P_u$) with crack width for an upward movement ($\delta$) of 2.5 mm. Pullout load required to be applied on a GPA for an upward movement ($\delta$) of 2.5 mm increased with increasing crack width.
8.4. CONCLUSIONS

Foundations in expansive soils are subjected to alternate swelling and shrinkage, and their engineering behaviour depends on the degree of swelling and shrinkage of the clay.
bed. Granular pile-anchors (GPAs) are a recent foundation technique devised for expansive soils. Study of engineering behaviour of GPAs subjected to swelling and shrinkage is important. Two series of pullout tests were conducted: (i) one on GPAs subjected to varying swelling and (ii) the other on GPAs subjected to varying shrinkage. The following are the important conclusions drawn from the experimental study:

1. Heave of GPA-reinforced expansive clay beds increased with increasing water content in the clay beds. The heave profiles of the clay beds were close to one another, the clay beds being identical. The degrees of saturation of the clay beds were 20%, 37%, 51%, 67%, 82%, 98% and 100% respectively for water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%. The degree of saturation and heave increased with water content.

2. The clay bed at a water content of 70% indicated 100% degree of saturation, and hence, the corresponding pullout test data indicated failure. The pullout test data of GPAs tested at lower water contents indicated that pullout behaviour of the GPAs improved as the test water content decreased.

3. Shear resistance to uplift, a function of $c'$ and $\phi'$ of the cylindrical GPA-clay interface, increased with decreasing water content. $c'$ increased and $\phi'$ decreased with increasing water content of the clay bed. $P_u$ for an upward movement ($\delta$) of 0.5 mm increased with increasing $\phi'$, and decreased with increasing $c'$. $P_u$ required to be applied on the GPAs for a given upward movement ($\delta$) of 0.5 mm was respectively 240N, 215N, 185N, 170N, 145N, 130N and 120N for test water contents of 10%, 20%, 30%, 40%, 50%, 60% and 70%.

4. Heave of GPA-reinforced expansive clay bed decreased in comparison to that of unreinforced clay bed. Shrinkage (mm) increased with increasing time period in both GPA-reinforced and unreinforced clay beds. Shrinkage (mm) recorded in the case of unreinforced clay bed ($n = 0$) for 15 days, 30 days and 45 days was higher than that recorded in the case of GPA-reinforced expansive clay beds ($n = 1$). Shrinkage was also effectively controlled in the case of GPA-reinforced expansive clay beds. Shrinkage (mm) recorded in unreinforced expansive clay bed ($n = 0$) was 18.7mm for a shrinkage period of 45 days, whereas shrinkage
recorded in GPA-reinforced expansive clay bed was respectively equal to 7.8 mm, 3.76 mm and 1.58 mm for period of 45 days, 30 days and 15 days.

5. Pu–δ behaviour improved with increasing shrinkage period. Pu–δ curve for GPA at 0-day shrinkage period indicated failure, and the Pu–δ curves of GPAs at longer shrinkage periods shifted upwards and did not indicate failure. The uplift load (Pu) required to be applied on a GPA for a given upward movement (δ) increased with increasing shrinkage period. For example, the uplift loads (Pu) on GPAs subjected to shrinkage for 0, 15, 30 and 45 days were respectively 100N, 110N, 140N and 270N for an upward movement (δ) of 2.5 mm.

6. Vertical shrinkage (mm) also increased with increasing shrinkage period, and resulted in a correlation with Pu. Water content decreased at all depths with increasing shrinkage period.

7. Crack width at the top of the clay bed increased with increasing shrinkage period. Further, pullout load (Pu) required to be applied on a GPA for an upward movement (δ) of 2.5 mm increased with increasing crack width.