

CHAPTER 5

SINGLE COLUMN MODEL TESTS

5.1 General

In this chapter a set of physical axisymmetric model tests have been conducted on single geopolymer stabilized soil columns (GPSCs) in very soft soil under static and cyclic loading conditions. The DSM column was constructed with geopolymer as a binder. A set of instrumented 1-g axisymmetric model tests were performed on single end-bearing and floating GPSC in very soft kaolin clay with an undrained shearing strength of 5-5.5 kPa, subjected to static loading conditions. Since the bearing capacity was much lower in a single floating GPSC; therefore, model tests under cyclic loading were performed on end-bearing columns only. Furthermore, a comparison of the static and cyclic behavior of GPSC-treated soft soil at the same area replacement ratio was done. The primary parameters examined include the effect of the l/h ratio (end-bearing and floating GPSC) under static loading, the area replacement ratio (A_r) under static and cyclic loading, and the effect of CSR under cyclic loading.

5.2 Test series

The details of experiments conducted on unimproved and improved soft soil ground with single end-bearing and floating DSM columns are given in Table 5.1. The test on an unimproved soft soil bed was conducted as a reference test under static and cyclic loading. A total of seven static loading tests were performed on improved ground consisting of four improved grounds with end-bearing columns having different area replacement ratios and three improved grounds with floating columns. Eight experiments were conducted under cyclic loading conditions consisting of four

improved grounds with end-bearing columns having different area replacement ratios and four improved grounds with different cyclic stress ratios.

Table 5.1 Summary of the model tests.

Test no.	d (mm)	l (mm)	A_r (%)	l/h	CSR	q_c (kPa)	Column type	Loading pattern
1.	-	-	-	-	-	-	-	Static
2.	-	-	-	-	0.5	100.65	-	Cyclic
3.	30	300	9	1	-	-	End-bearing	Static
4.	40	300	16	1	-	-	End-bearing	Static
5.	50	300	25	1	-	-	End-bearing	Static
6.	60	300	36	1	-	-	End-bearing	Static
7.	50	225	25	0.75	-	-	Floating	Static
8.	50	150	25	0.5	-	-	Floating	Static
9.	50	105	25	0.35	-	-	Floating	Static
10.	30	300	9	1	0.5	100.65	End-bearing	Cyclic
11.	40	300	16	1	0.5	100.65	End-bearing	Cyclic
12.	50	300	25	1	0.5	100.65	End-bearing	Cyclic
13.	60	300	36	1	0.5	100.65	End-bearing	Cyclic
14.	50	300	25	1	0.2	40.26	End-bearing	Cyclic
15.	50	300	25	1	0.35	70.45	End-bearing	Cyclic
16.	50	300	25	1	0.75	150.97	End-bearing	Cyclic
17.	50	300	25	1	1	201.3	End-bearing	Cyclic

Note: d = diameter of geopolymer stabilized soil column (GPSC); l = length of GPSC; A_r = area replacement ratio; h = height of the soft soil bed; CSR = cyclic stress ratio; q_c = cyclic stress.

GGBS and dolomite-based geopolymer were used with liquid sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) as alkali activators. The ratio of GGBS and dolomite was 80:20, and the NaOH: Na_2SiO_3 ratio was 25:75. The NaOH solution was prepared with molarity of 8M, and the alkali activator and binder ratio was 1. The binder

content of 20% was mixed with the soil. The above geopolymer mix was found to provide maximum strength.

5.3 Results and Discussions

5.3.1 Response under Static Loading

5.3.1.1 Behavior of GPSC with Different Area Replacement Ratios under Static Loading

Fig. 5.1 presents the vertical pressure versus footing settlement response obtained from the model tests on the composite ground improved with 30 mm, 40 mm, 50 mm, and 60 mm diameter columns with area replacement ratios of 9%, 16%, 25%, and 36%, respectively. The increase in diameter is required to increase the area replacement ratio keeping the diameter of the footing constant. Punching shear failure was observed in an unimproved soil model with an ultimate bearing capacity of 25.76 kPa at 50 mm settlement. For all area replacement ratios, the stress-settlement curve of soft soil improved with end-bearing GPSC resembled the general shear failure, providing a clear indicator of the peak stress. The increase in the area replacement ratio causes an increase in stress on the composite ground and a decrease in the vertical displacement at the peak stress, i.e., failure. The possible reason for this could be that increased A_r makes the composite ground stiffer and can support higher stresses in less vertical footing settlement. The ultimate bearing capacity (q_{ult}) for A_r of 9%, 16%, 25%, and 36% was 62.4 kPa, 101.23 kPa, 201.3 kPa, and 248.9 kPa, respectively, which were the peak values obtained from the graph. As the peak value of vertical stress is reached, the composite ground fails as it cannot withstand further stress, and the stress tends to reduce (Terashi and Tanaka 1981; Yin and Fang 2010). As the area replacement ratio increases, a more significant proportion of applied load is supported by the GPSC, which is a comparatively stronger material than the surrounding soil. Therefore, the

stiffness and failure stress of the improved ground increase as the area replacement ratio increases. Also, the higher the A_r , the higher the cross-sectional area of the GPSC; hence, the better the performance of the composite ground.

The bearing capacity ratio of the untreated and GPSC-treated soft soil with different A_r is shown in Fig. 5.2(a). The bearing capacity ratio is defined as the ratio of the ultimate bearing capacity (q_{ult}) and undrained shear strength of the soft soil in the model test. The bearing capacity ratio (q_{ult}/c_{us}) significantly increased by 64.04% and 104.98%, with an increase in A_r from 9% to 16% and 16% to 25%, respectively. The maximum increase in q_{ult}/c_{us} was observed at A_r of 25%, and the further increase in A_r from 25% to 36% resulted in an increase of 20.39% in q_{ult} , indicating that the impact of increasing A_r above 25% is substantially low.

The degree of improvement obtained with the GPSC as a column in soft soil with different area replacement ratios compared to untreated soil is presented in Fig. 5.2(b). The achieved degree of improvement is defined as the bearing improvement ratio (q_s/q_{us}), which is the ratio of q_{ult}/c_{us} of GPSC-treated soil (q_s) to q_{ult}/c_{us} of untreated soil (q_{us}). The bearing improvement ratio was 2.28, 3.74, 7.67, and 9.24 for A_r of 9%, 16%, 25%, and 36%, respectively.

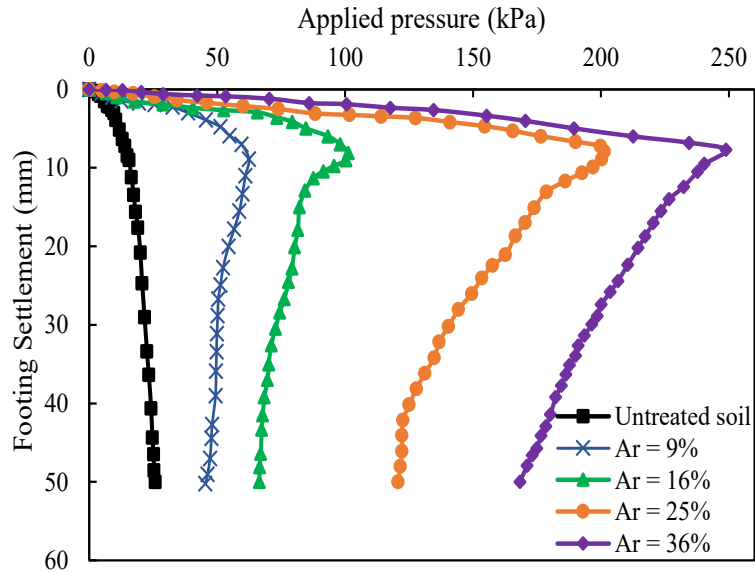


Fig. 5.1 Effect of area replacement ratio (A_r) on failure stress of the untreated ground and single end-bearing ($l/h = 1$) GPSC improved ground.

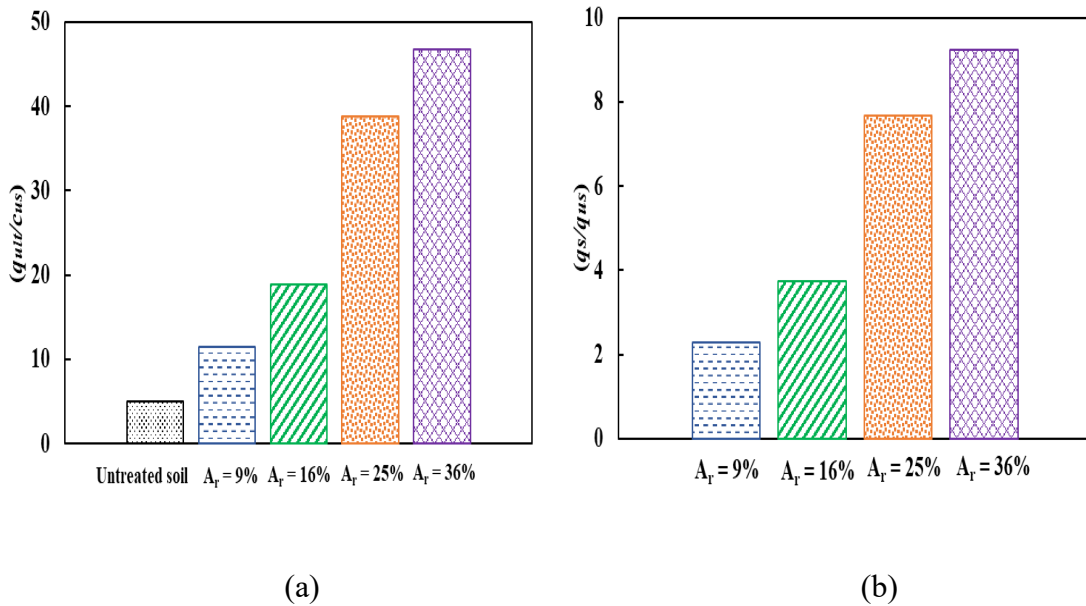


Fig. 5.2 (a) Bearing capacity ratio of the unimproved ground and single end-bearing GPSC improved composite ground with different A_r and (b) Bearing improvement ratio at the failure of the single end-bearing GPSC improved ground with different A_r .

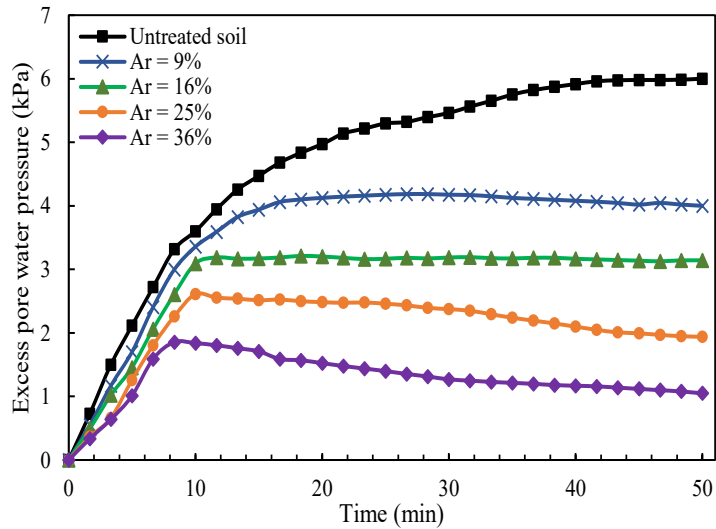
Fig. 5.3(a) shows the change in excess pore water pressure with time elapsed in the middle of the soil bed at a radial distance of 50 mm from the center of the column in the soft soil with different area replacement ratios. The excess pore water pressure

response of the untreated soil was also obtained and found to increase with time. When vertical stress is applied on improved ground, the stresses are shared by the GPSC and the surrounding soil. With the increase in vertical stress, the excess pore water pressure increases with time, and just before the failure of the GPSC, the excess pore water pressure increases sharply due to increased stress on the soil and reaches the peak value. After failure, the applied load decreases, consequently reducing stresses in the clay and excess pore water pressure. Also, the cracked GPSC acts as a drain, which results in the dissipation of excess pore water pressure (Horpibulsuk et al. 2012). With the increase in A_r , the stiffness of the GPSC increases, and the GPSC carries higher stresses than the surrounding soil; as a result, the excess pore water pressure in the soil reduces.

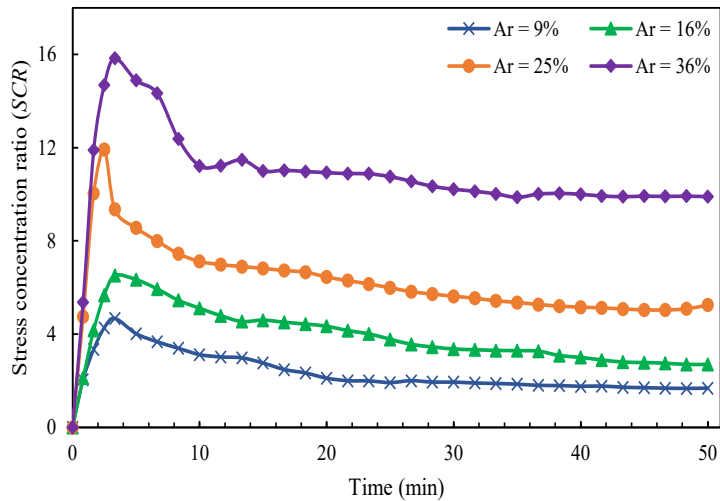
As the soft soil bed is improved with the column and subjected to static load, the column and the surrounding soft soil experience different stress distributions. The stress distribution between the column and the surrounding soil significantly influences the settlement behavior of the ground. The stress concentration ratio (SCR) is the ratio of stress on the column to the stress on the surrounding soil. $SCR > 1$ indicates that the stress carried by the column is higher than the stress on the surrounding, $SCR = 1$ indicates the column and the surrounding soil equally share the applied stress, and $SCR < 1$ indicates the stress on the surrounding soil is higher than the column (Yun-min et al. 2008). The SCR depends on various factors such as the stiffness of the column, soil properties, rate of loading, type of loading, area replacement ratio, length of the column, etc.

The change in SCR with time for different area replacement ratios is plotted in Fig. 5.3(b). As the static loading was applied, the SCR increased with time, attaining a peak SCR value and gradually decreasing with time, achieving a steady value. The same pattern of SCR has been reported by (Han and Gabr 2002; Zhao et al. 2023). The SCR

was found to increase with an increase in A_r because as the A_r increases, the stiffness of the column increases, resulting in a higher vertical stress-bearing capacity of the column.



(a)



(b)

Fig. 5.3 (a) Variation in excess pore water pressure with time for untreated and single end-bearing GPSC improved soft soil with different A_r and (b) Variation in stress concentration ratio with time for single end-bearing GPSC improved soft soil with different A_r .

5.3.1.2 Behavior of GPSC with Different l/h Ratios under Static Loading

Fig. 5.4 shows the vertical stress–settlement responses of the untreated soil with the floating GPSC-treated soil with l/h ratio of 0.35, 0.5, and 0.75 and the end-bearing GPSC-treated soil with l/h ratio of 1 at an area improvement ratio of 25%. The figure illustrates that the ultimate bearing capacity of floating GPSC improved ground was better than untreated soft soil ground as floating columns facilitate load transfer to deeper depth, and the performance of end-bearing GPSC improved ground was better than floating GPSC as higher end-bearing stresses are mobilized in the former. It can be seen that the ground improved with floating GPSC of different lengths have ductile behavior. With the increase in the GPSC length, the performance of the composite ground improved due to higher skin interactions between the GPSC and the surrounding soft soil. It should be noted that the ultimate bearing capacity of the end-bearing GPSC improved soil showed clear peak failure; therefore, the q_{ult} was taken at failure, whereas for untreated and floating GPSC improved soil, there was no evident peak; therefore, the q_{ult} was considered at 50 mm settlement. The ultimate bearing capacity (q_{ult}) for l/h of 0.35, 0.5, 0.75, and 1 was 39.86 kPa, 49.55 kPa, 77.6 kPa, and 201.3 kPa, respectively. As the length of the GPSC increases, the stiffness and failure stress of the improved ground increases. Compared to untreated soil, the q_{ult} of floating GPSC improved soil increased by 49.14%, 81.62%, and 181.83% for l/h ratios of 0.35, 0.5, and 0.75, respectively.

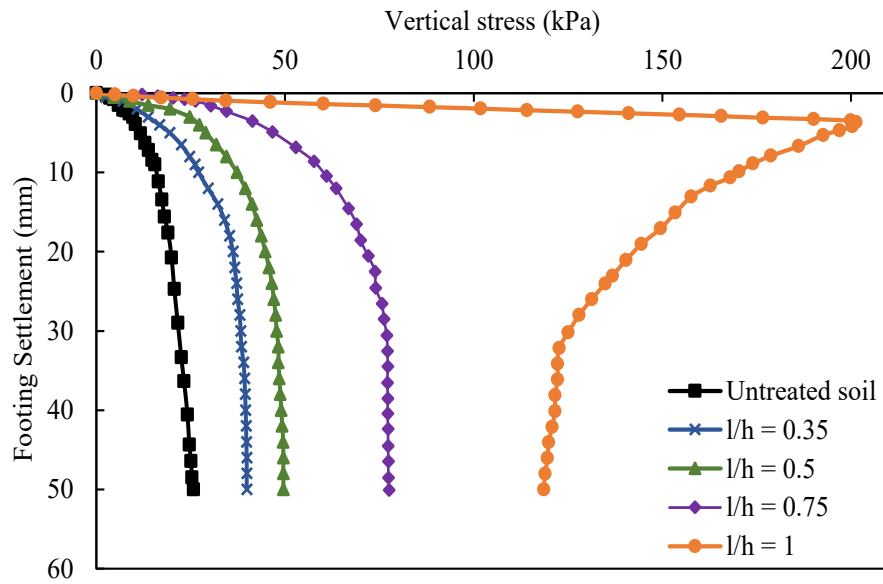


Fig. 5.4 Effect of l/h ratio of the column on failure stress of the untreated ground and single GPSC improved ground ($A_r = 25\%$).

The bearing capacity ratio (q_{ult}/c_{us}) of the untreated and GPSC-treated soft soil with different l/h ratios is shown in Fig. 5.5(a). In the case of the untreated soil bearing capacity ratio was 5.05 kPa. The bearing capacity ratio increased by 21.78% and 55.17%, with an increase in the l/h ratio from 0.35 to 0.5 and 0.5 to 0.75, respectively. A significant increase of 172.4% was obtained when the l/h ratio was increased from 0.75 (floating GPSC) to 1 (end-bearing GPSC). Fig. 5.5(b) presents the improvement achieved with the installation of GPSC in soft soil with different l/h ratios compared to untreated soil. The bearing improvement ratio was 1.49, 1.82, 2.82, and 7.67 for l/h ratios of 0.35, 0.5, 0.75, and 1, respectively. A significant change in the bearing improvement ratio was observed in end-bearing GPSC-improved soft soil compared to floating GPSC-improved soft soil.

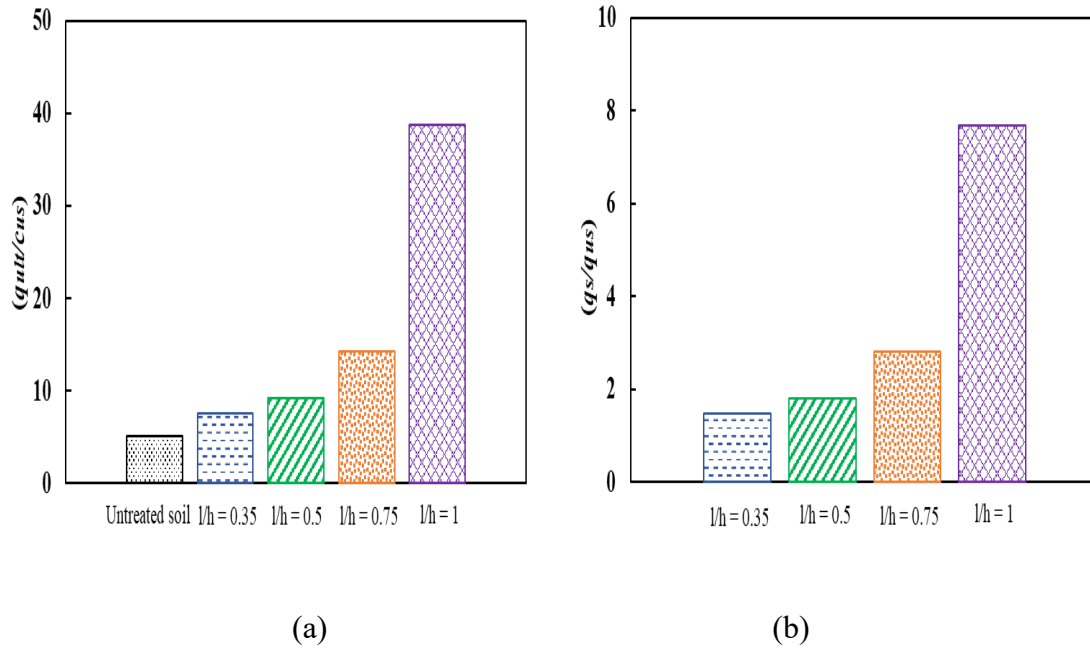
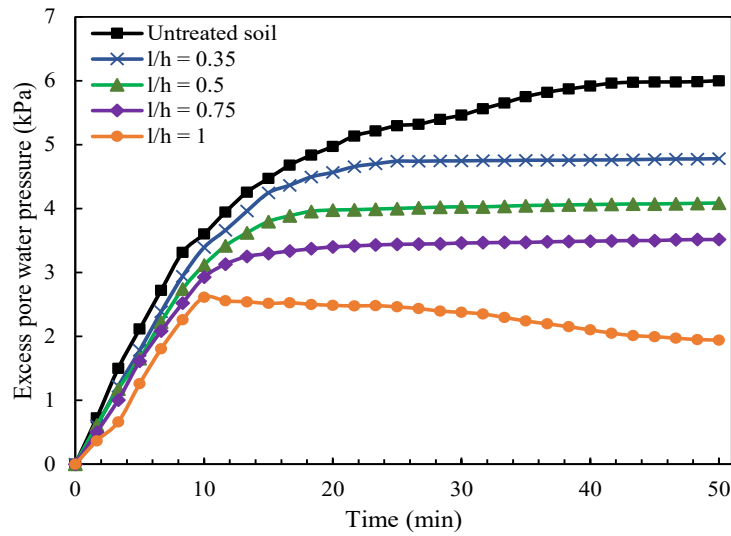


Fig. 5.5 (a) Bearing capacity ratio of the unimproved ground and single GPSC improved ground with different l/h ratios ($A_r = 25\%$) and (b) Bearing improvement ratio at the failure of the single GPSC improved ground with different l/h ratios ($A_r = 25\%$).

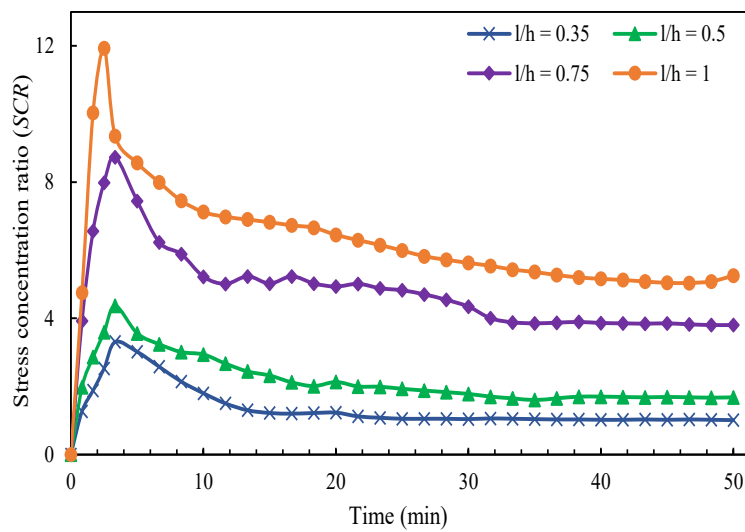
The change in excess pore water pressure with time elapsed for different l/h ratios at an A_r of 25% is shown in Fig. 5.6(a). The excess pore water pressure decreased with an increase in the length of the GPSC column. With an increase in the length of the GPSC, the vertical stress on the GPSC increases, resulting in reduced stress on the surrounding soil. As the stress on the surrounding soil reduces, the excess pore water pressure on the soil decreases.

Fig. 5.6(b) shows the change in SCR with time for different l/h ratios. It was found that the SCR value increased with the increase in the l/h ratio. For l/h ratios of 0.35 and 0.5, the SCR reaches its peak value of 3.31 and 4.37, respectively. After attaining peak value, SCR tends to decrease and reaches a steady state with SCR values of 1.01 and 1.67 for l/h ratios of 0.35 and 0.5, respectively. SCR value of 1.01 indicates that the column and the surrounding soil share the stress equally; the stress is ultimately

transferred from the column to the surrounding soil, and the column cannot take any further load.



(a)



(b)

Fig. 5.6 (a) Variation in excess pore water pressure with time for untreated and single GPSC improved soft soil with different l/h ratios ($A_r = 25\%$) and (b) Variation in stress concentration ratio with time for single GPSC improved soft soil with different l/h ratios ($A_r = 25\%$).

5.3.2 Response under Cyclic Loading

5.3.2.1 Behavior of GPSC with Different Area Replacement Ratios (A_r) under Cyclic Loading

Fig. 5.7 shows the settlement response with the number of cycles under cyclic stress of 100.65 kPa (CSR = 0.5) for untreated and end-bearing GPSC-treated soil with A_r of 9%, 16%, 25%, and 36%. It was observed that the untreated soil model failed with 50 mm settlement within 245 cycles only. With the installation of GPSC, a decrease in accumulated settlement was observed as the area replacement ratio was increased. The accumulated settlement after 10,000 cycles was 13.47 mm and 7.12 mm for an area replacement ratio of 25% and 36%. On reducing the area replacement below 25%, the model failed and reached a settlement of 50 mm. The comparison of the settlement response with the increase in the number of cycles is shown in Fig. 5.8. For untreated soil, 27.5 mm of settlement is reached within 100 cycles. In contrast, the column installation with an A_r of 9% and 16% reduced the settlement to 11.8 mm and 9.56 mm within 100 cycles, showing much improvement in bearing cyclic stress. With further increase in A_r to 25% and 36%, the settlement reduced to 4.4 and 3.56 mm in 100 cycles. The untreated soil reached 50 mm in 245 cycles, whereas with the column installation of A_r of 9%, the 50 mm settlement was attained within 630 cycles. For A_r of 16%, 18.8 mm settlement was obtained in 1000 cycles, and 50 mm settlement reached within 6590 cycles. It was observed that for higher A_r of 25% and 36%, maximum settlement is reached within 500 cycles, and the settlement is gradually stabilized with a further increase in the number of cycles.

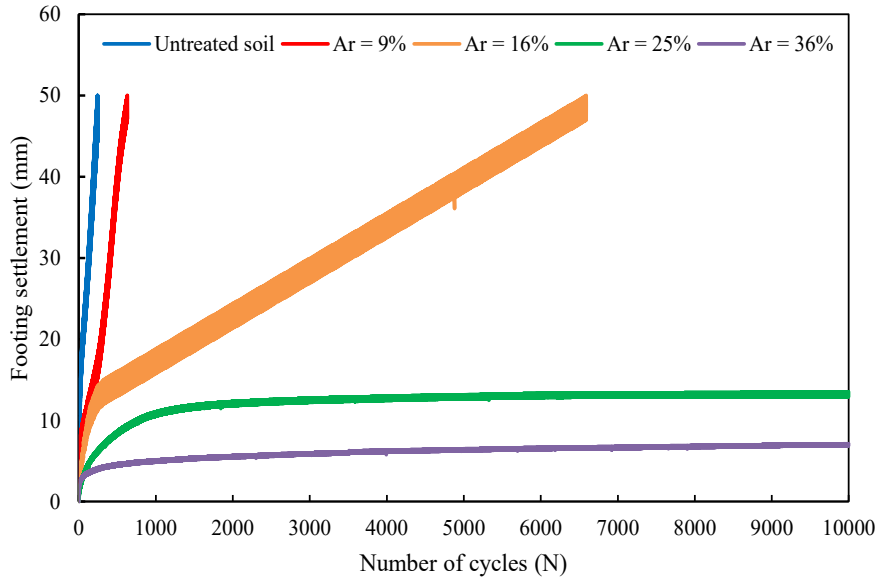


Fig. 5.7 Settlement performance of untreated and single end-bearing ($l/h = 1$) GPSC-treated soil with the number of cycles for different A_r under cyclic stress of 100.65 kPa (CSR = 0.5).

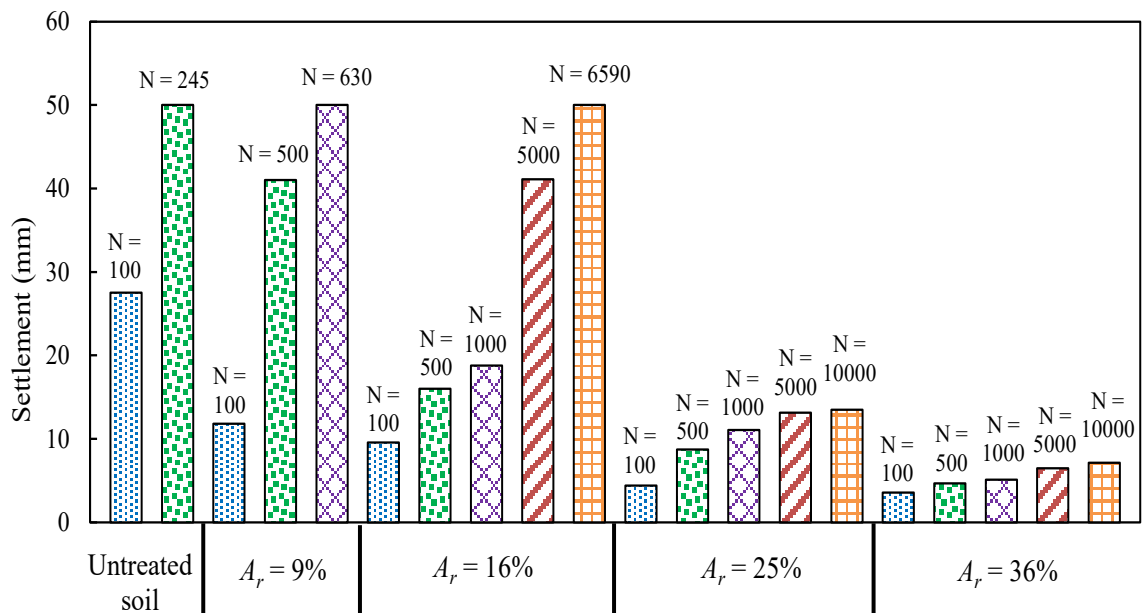
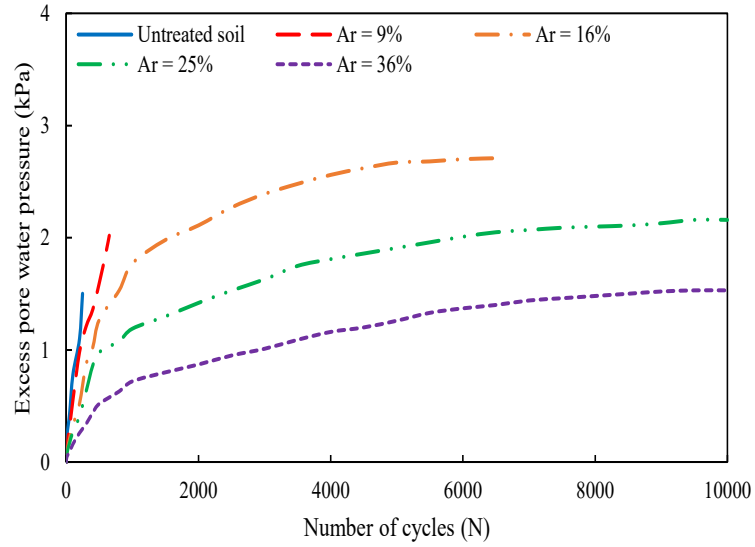


Fig. 5.8 Comparison of settlement response of untreated and GPSC-treated soil for different A_r with the increase in the number of cycles.

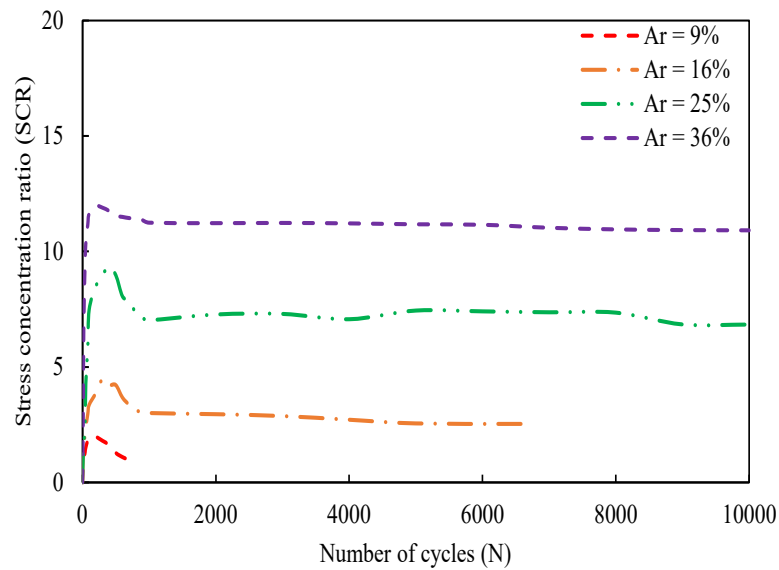
Fig. 5.9(a) presents the variation of excess pore water pressure with the number of cycles for different area replacement ratios and l/h of 1. The excess pore water

pressure response of the untreated soil under cyclic loading increased with time. The excess pore water pressure under cyclic loading was observed to be lower than that in static loading. The reason could be that under cyclic loading, the same stress is applied for a number of cycles, whereas in static loading, the load increases with time, resulting in more excess pore water pressure dissipation. The accumulation of excess pore water pressure increased with the increase in A_r . With the installation of GPSC of $A_r = 9\%$, the settlement increased quickly with the number of cycles indicating that the GPSC could not take the cyclic stress and failed. This resulted in the transfer of stress from GPSC to the surrounding soil; therefore, the excess pore water pressure increased with the number of cycles. The increase in A_r increases the stiffness of the GPSC, and the GPSC can take that cyclic stress with less settlement. As a result, stress on the surrounding soil decreases, reducing the excess pore water pressure in the soil.

The variation of SCR with the number of cycles for different area replacement ratios is presented in Fig. 5.9(b). The SCR was increasing with an increase in A_r . A higher stress concentration ratio indicates that stress on the column was notably higher than on the surrounding soil. It was observed that SCR increases quickly within the first few cycles and then reduces and reaches a steady state with the increase in loading cycles. For A_r of 9%, SCR reached the peak value of 1.96 in 200 cycles, indicating that GPSC was taking a higher load than the surrounding soil. With the further increase in cyclic loading, the SCR reduced to 1, indicating that the column failed and stress is equally shared by the column and the soil. With the increase in A_r , stress taken by the column increased, and therefore the SCR value increased. At higher A_r , the SCR in the steady stage was marginally lower than the peak SCR value.



(a)



(b)

Fig. 5.9 (a) Variation in excess pore water pressure with the number of cycles for untreated and single end-bearing GPSC improved soft soil with different A_r and (b) Variation in stress concentration ratio with the number of cycles for single end-bearing GPSC improved soft soil with different A_r .

5.3.2.2 Behavior of GPSC under Different Cyclic Stress Ratios (CSR)

The effect of CSR on the settlement response of the end-bearing ($l/h = 1$) GPSC-treated soil with an A_r of 25% is shown in Fig. 5.10. The increase in cyclic stress would promote the accumulated settlement. When the CSR increases from 0.2 to 0.35, the settlement increases from 4.11 mm to 9.58 mm in 10,000 cycles. At the CSR of 0.5, the settlement was 13.47 mm in 10,000 cycles, and a further increase in CSR settlement of 50 mm was reached before the completion of 10,000 cycles. It indicates that a CSR of 0.5 was the threshold CSR, and above a CSR of 0.5, the settlement was more profound. The comparison of the settlement response of different CSR values with the increase in the number of cycles is presented in Fig. 5.11. It was observed that up to a CSR value of 0.5, more than 50% of settlements developed within 500 cycles, and then it was gradually stabilized with a further increase in the number of cycles. At CSR of 0.75, 50 mm settlement was reached within 7640 cycles, whereas at CSR of 1, 50 mm settlement was obtained within 1475 cycles.

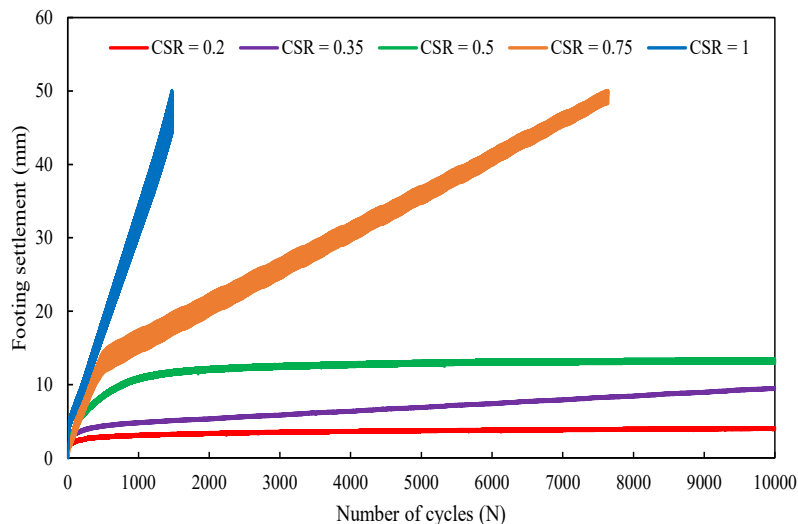


Fig. 5.10 Settlement performance of single end-bearing GPSC-treated soil with an A_r of 25% for different CSR values under cyclic loading.

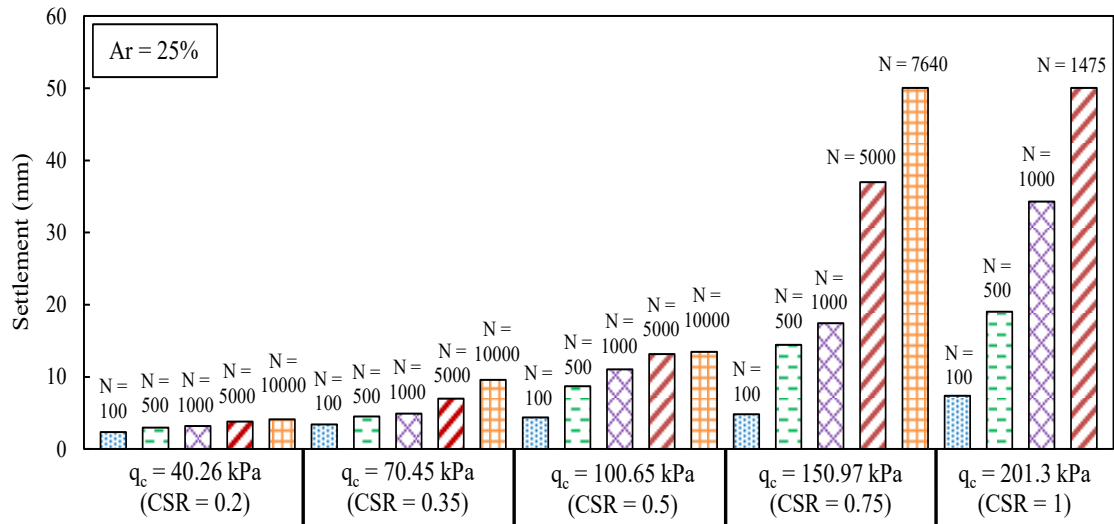
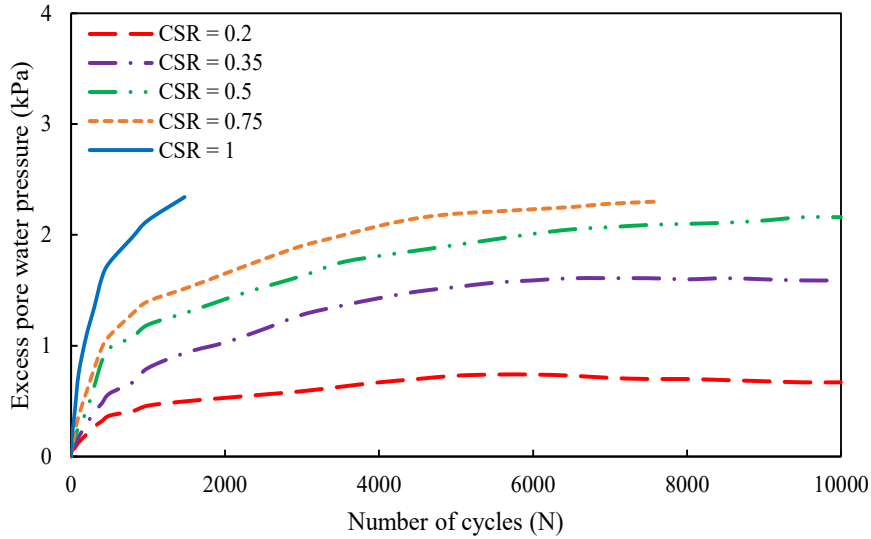


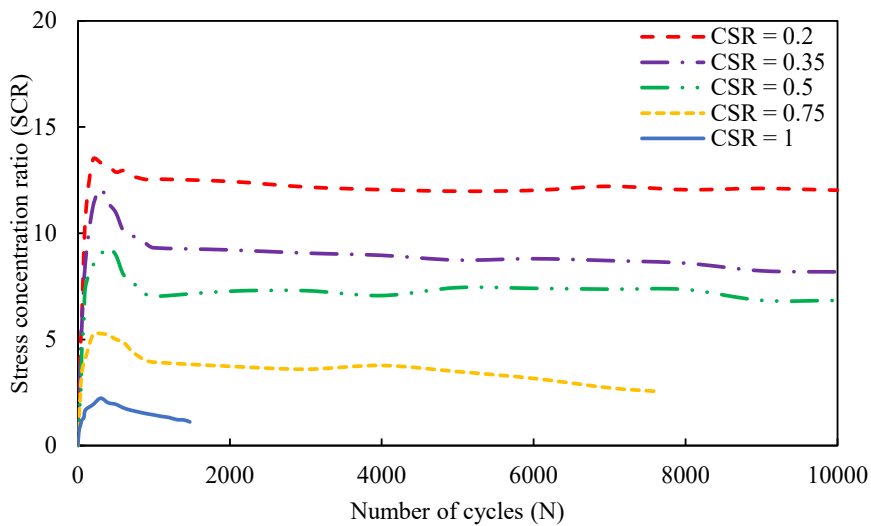
Fig. 5.11 Comparison of settlement response of GPSC-treated soil for different CSR values and A_r of 25% with the increase in the number of cycles.

The effect of CSR on the variation in excess pore water pressure with the number of cycles at an A_r of 25% is presented in Fig. 5.12(a). Results show that the increase in CSR value leads to a larger accumulation of excess pore water pressure. With an increase in the CSR value, the vertical stress on the composite ground increases, resulting in higher stress on the surrounding soil. As the stress on the surrounding soil increases, the excess pore water pressure on the soil increases.

Fig. 5.12(b) shows the change in SCR with the number of cycles for different CSR values at an A_r of 25%. The increase in cyclic load resulted in the reduction in SCR peak value. With the increase in CSR, stress on the improved ground increases, which increases the stress on GPSC, and GPSC fails. At the time of GPSC failure, the stress is transferred to the surrounding soil; therefore, after attaining a peak value SCR gradually starts reducing. At lower CSR value, failure of GPSC did not occur, and stress transferred on the surrounding soil reduced; therefore, after getting peak SCR value, the decrease in SCR is not that prominent and attains a constant SCR (little less than peak SCR value) even after 10,000 loading cycles.



(a)



(b)

Fig. 5.12 (a) Variation in excess pore water pressure with the number of cycles for single end-bearing GPSC improved soft soil with different CSR values and (b) Variation in stress concentration ratio with the number of cycles for single end-bearing GPSC improved soft soil with different CSR values.

5.3.2.3 Settlement Response under Cyclic Loading vs Static Loading

The measured cyclic settlement after 10,000 cycles was compared with static loading settlement at the same stress of 100.65 kPa, and the results obtained are

presented in Fig. 5.13. As the ultimate bearing capacity of the model ground stabilized with GPSC of A_r of 9% is less than 100.65 kPa, therefore A_r of 9% was not considered in the comparison. The impact of cyclic loading was higher when the area replacement ratio was less. With the increase in A_r from 16% to 25%, the settlement under static loading of 100.65 kPa was reduced by 59.11%, whereas under cyclic loading of 100.65 kPa for 10,000 cycles, the settlement was reduced by 73.11%. Similarly, with the increase in A_r from 25% to 36%, the settlement under static loading was reduced by 41.17%, whereas under cyclic loading, the settlement was reduced by 47.14%. The settlement reduction was higher under cyclic loading with the increase in A_r . The rate of settlement reduction was higher when A_r was increased from 16% to 25%. This implies that GPSC inclusion with an A_r of 25% in soft soil effectively improves soft soil under static and cyclic loading.

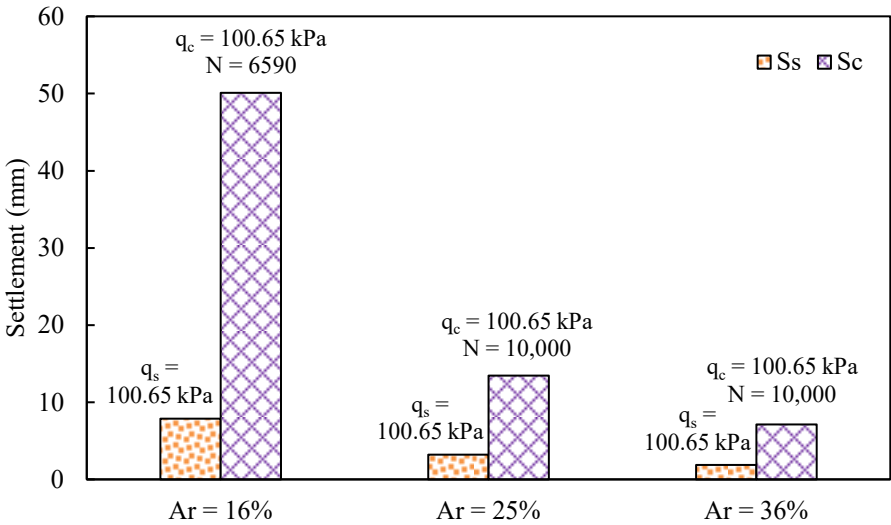


Fig. 5.13 Comparison of settlement under static and cyclic loading of 100.65 kPa for A_r of 16%, 25%, and 36%.

5.4 Summary

This chapter presents the results of a set of designed model tests on GPSC-improved ground that have been conducted to study the static and cyclic loading behavior of the improved ground, considering different parameters.

The stiffness and bearing capacity of the improved composite ground was enhanced by the addition of a geopolymer-stabilized soil column (GPSC) to soft soil ground. With an increase in A_r from 16% to 25%, the bearing capacity ratio increased by a maximum of 104.98%. When comparing end-bearing GPSC-improved soft soil to floating GPSC-improved soft soil, a notable change in the bearing improvement ratio was observed.

As the area replacement ratio increases and CSR decreases, a decrease in cumulative settlement under cyclic loading was observed. The threshold CSR value was found to be 0.5, and an increase in CSR resulted in a higher settlement. The SCR increased as A_r , and the amplitude of the cyclic stress increased during cyclic loading. Under static loading, a similar trend of SCR has been observed with an increase in the A_r and l/h ratio. The addition of GPSC reduced the development of excess pore water pressure in the nearby soil.