CHAPTER 5

UNREINFORCED AND GEOCELL-REINFORCED SAND BED UNDER REPEATED LOADS

5.1 Introduction

The response of square footing on unreinforced and geocell-reinforced sand beds under repeated loads is presented and discussed in this chapter. The test series J1 and J2 are carried out to investigate the effect of initial monotonic load level on the footing behaviour for both unreinforced and reinforced foundations. The study was conducted using different values of repeated load levels, expressed as a ratio of applied repeated pressure (q_d) to the ultimate bearing pressure (q_{ult}) of the unreinforced or reinforced soil, termed as repeated load ratio (q_d/q_{ult}). Four different repeated load ratios (q_d/q_{ult}) 20%, 40%, 70%, and 85% were used to study the response of footing supported on unreinforced and reinforced sand beds. Thereafter, forty-three numbers of different model tests (test series B2, C2, D2, E2, F2, and G2, Table 3.4) were conducted to investigate the influence of relative density of sand subgrade, depth of placement of geocell layer from the base of the footing, geocell pocket size, the height of geocell layer and width of geocell reinforcement on the performance improvement of reinforced sand beds under repeated loads.

To carry out the repeated load tests, at the beginning (in case of 1st cycle of loading), the load was increased in five small increments (steadily from zero) until reaching the pre-determined value (loading). Each load increment was maintained at a value until the dial gauge readings of footing settlements stabilized, i.e. up to a time when the rate of settlement (dial gauge readings) gets appreciably reduced to a value of 0.02 mm/min. The applied load was then decreased to zero value (unloading) in 15 minutes. This process of 1st cycle of loading-unloading took about 300 minutes. Thereafter, subsequent cycles of reloading and unloading were applied on the footing which was termed repeated loading. The deformation of soil beneath the footing due to repeated load only (i.e. the difference in settlement under the last cycle and first cycle of loading) is denoted as (s_{rep}) and is normalized with footing width (B) to express it in a non-dimensional form as s_{rep}/B (%).

5.2 Effect of geocell reinforcement layer

As discussed in the previous chapter (Chapter 4), the ultimate bearing capacity of unreinforced sand and geocell-reinforced sand beds are 91 kPa and 214 kPa, respectively. To assess the performance improvement of geocell-reinforced sand as compared to unreinforced sand under the same magnitude of repeated loading, a repeated loading test is conducted up to a predetermined pressure of 64 kPa, which is 70% of ultimate bearing capacity of unreinforced sand. The load is applied on the footing supported on both unreinforced and geocell-reinforced sand. The test results plotted in Fig. 5.1 and Fig. 5.2 show that the rate of change of both total settlement (s_t) and the repeated settlement (s_{rep}) of the loaded surface decreases as the number of cycles of load increases, and their response become almost stable after first 10 load cycles, especially for the geocell-reinforced sands. Suku et al. [121] have also reported a similar trend of observation for both reinforced and unreinforced soils under repeated loading.

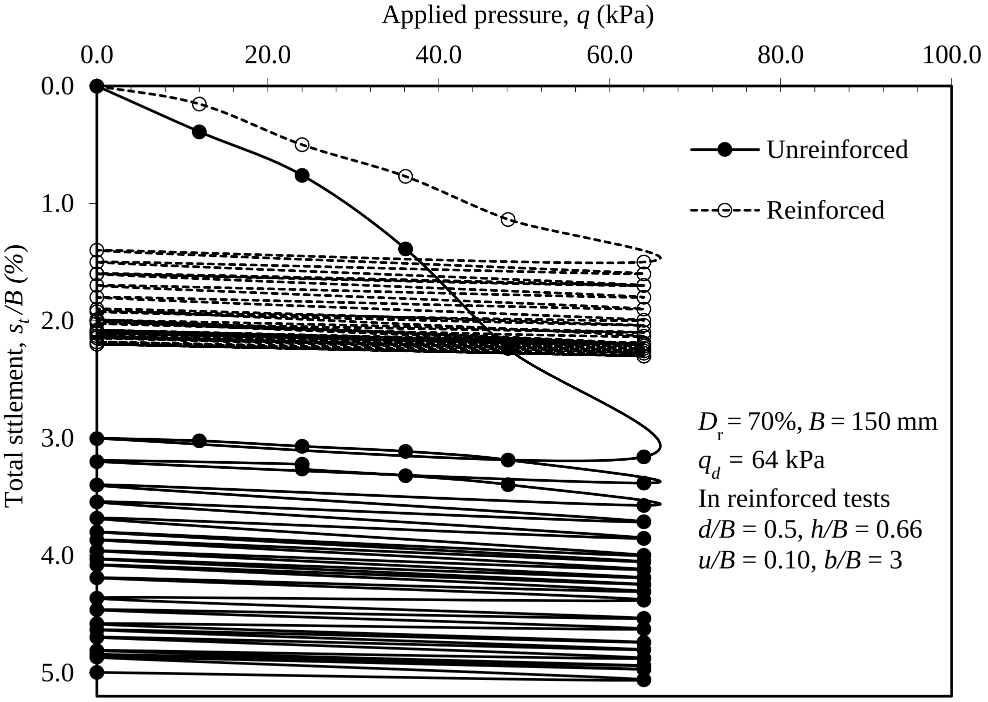


Fig. 5.1 Variation of total settlement (s_t /B) with applied repeated pressure (q) for unreinforced and geocell-reinforced soil beds at the equal intensity of repeated load

Fig. 5.1 also illustrates that the total settlement (s_t) under repeated loading reduces by 56% with the inclusion of geocell reinforcement which may be due to an upsurge in the stiffness of the reinforced sand bed compared to the unreinforced sand. The upsurge in stiffness of geocell-reinforced sand may be attributed to three factors, namely lateral confinement effect due to the 3-dimensional interaction between the encapsulated soil and the cellular structure, vertical dispersion effect due to the introduction of stiffer materials, and membrane effect because of an anchorage on both sides of the loaded soil [122, 144]. These three factors influence the distribution of the applied load over a wider area, instead of directly transferring them at the point of contact, and provide a composite slab with high flexural stiffness and load support capability within the geocell reinforcement [90, 130].

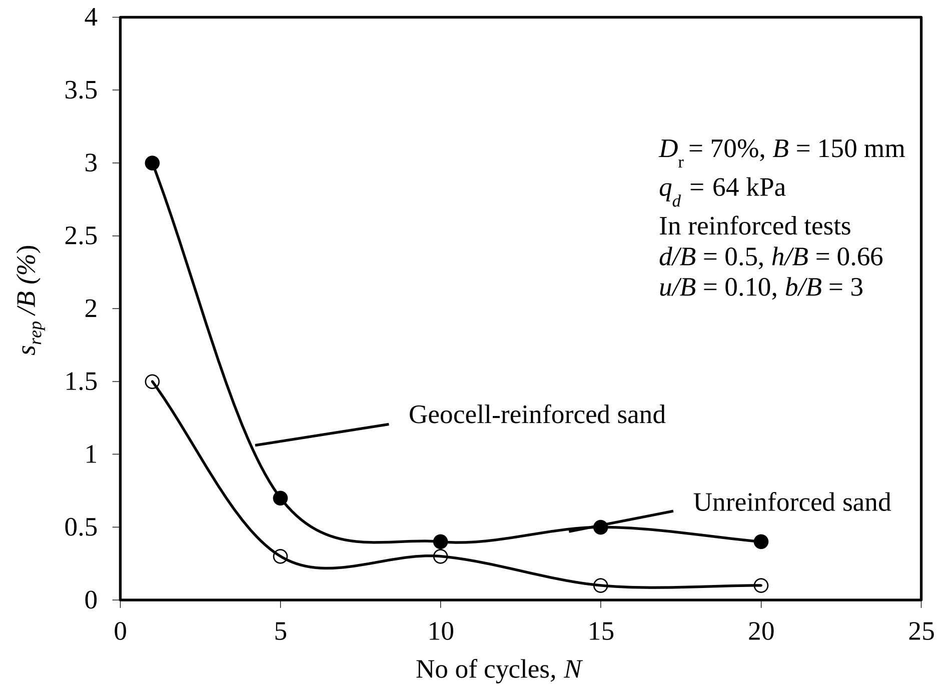


Fig. 5.2 Variation of repeated settlement (s_{rep} /B) with no. of cycle (N) for unreinforced and geocell-reinforced soil beds at the equal intensity of repeated load

Since there is a substantial increase in the ultimate bearing capacity of the sand bed with the inclusion of geocell reinforcement, it is of practical interest to study the behaviour of the geocell reinforced sand bed under repeated loading up to the same percentage of respective ultimate bearing capacities under unreinforced and reinforced conditions. With this in view, a series of repeated load tests were carried out up to 20%, 40%, 70%, and 85% of the respective ultimate bearing capacities, both for unreinforced and reinforced conditions of the sand bed as obtained from Fig. 4.2 and 4.12 (*i.e.* 91 kPa and 214 kPa for unreinforced and reinforced sand under square footing).

The variation of total settlement (s_t /B) with bearing pressure for initial static pressure amount (q_d/q_{ult}) equal to 70% of the ultimate bearing pressure for footing rested on unreinforced and geocell-reinforced sand subjected to repeated loads (i.e. q_d = 64 kPa for unreinforced, and q_d = 150 kPa reinforced sand) are presented in Fig. 5.3. Fig. 5.4(a-b) shows the variation of total settlement with applied pressure for different q_d/q_{ult} (= 20%, 40%, 70%, and 85%), both for unreinforced and reinforced sand beds. The figure demonstrates that with the steady increases in vertical stress, there is a rapid increase in settlement. Moreover, after the completion of each load cycle, the settlement increases and surpasses its previous maximum value.

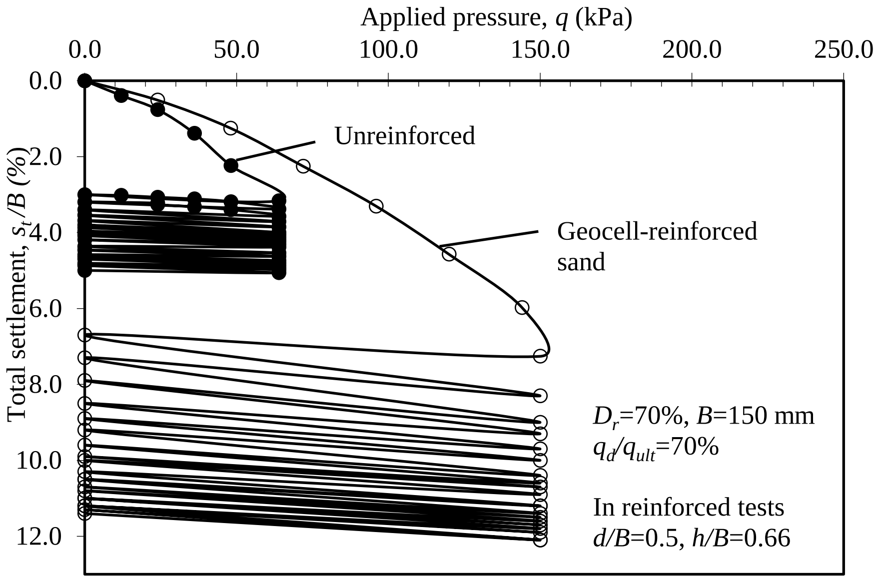
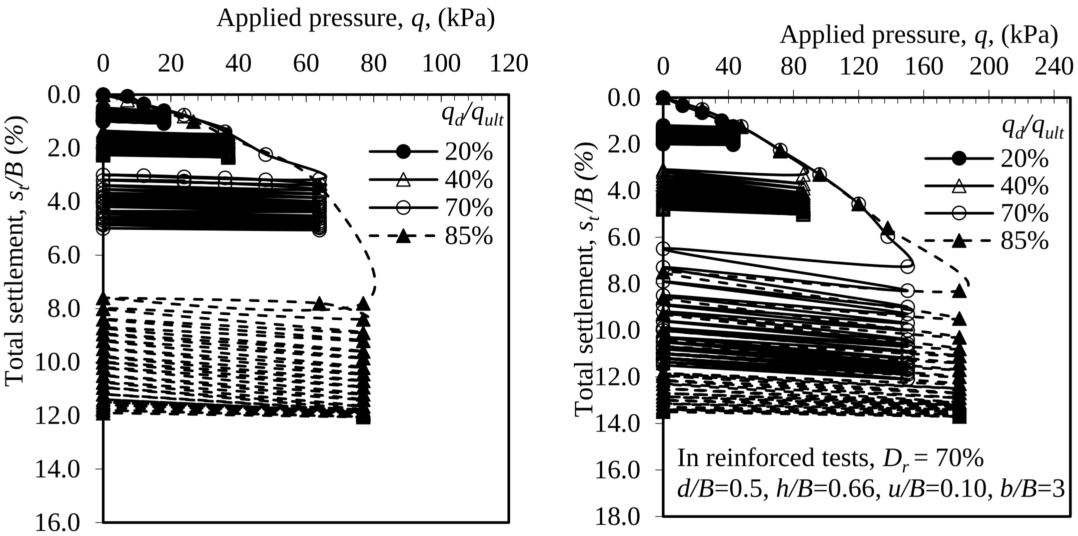


Fig. 5.3 Variation of total settlement (s_t /B) with applied pressure (q) for equal q_d/q_{ult} = 70%, and 20 cycles

It is also noticed that some recoverable settlement (elastic rebound) upon decreasing the load to zero (unloading) occurs. However, the settlements do not bounce back to their earlier value while unloading, and some permanent settlements remained on the footing. The settlement that occurred up to the final cycle of loading including all stages of loading is termed as cumulative or total settlement (s_t). The permanent total settlement is also observed to increase with the increase of the number of load cycles and it is more prominent for the first few cycles of loads. The test results of the total settlement of footing resting on unreinforced and geocell-reinforced sand are discussed in the following sections.



(a) (b)

Fig. 5.4 Variation of s_t/B with applied pressure (q) for q_d/q_{ult} = 20%, 40%, 70% & 85% after 20 cycles of load: (a) Unreinforced; (b) geocell-reinforced sand beds

5.2.1 Effect of initial static load level

The test series J1 (Table 3.4) is conducted on unreinforced medium-dense sand (D_r = 70%) while the test series J2 (Table 3.4) is performed on geocell-reinforced sand at the same density. One layer of geocell made from woven geotextile with d/B = 0.50, h/B = 0.66, u/B = 0.1, and b/B = 3 is used as a reinforcement material. Fig. 5.5 presents the variation of repeated settlement, (s_{rep}/B), with repeated load ratio, q_d/q_{ult}, for the case of unreinforced and geocell-reinforced sand after the application of 20 cycles of load. It can be seen that with increasing repeated load ratio, q_d/q_{ult}, the repeated settlement increases. It is also observed that a higher value of the repeated settlement, (s_{rep}/B), is obtained for q_d/q_{ult} of 70% and 85%, as compared to q_d/q_{ult} of 20% and 40%. Furthermore, it is noted that a higher repeated settlement of the geocell-reinforced bed than that of the unreinforced bed for the same initial repeated load ratio takes place. This can be attributed to the fact that for both the cases of reinforced and unreinforced beds, the repeated load tests are conducted at the same normalized repeated load ratio, q_d/q_{ult}. Since the ultimate bearing capacity for reinforced sand is much higher than that of unreinforced sand (*i.e.* 2.35 times the ultimate bearing capacity of unreinforced sand), therefore, both the initial static load and the repeated load levels are significantly higher for reinforced sand as compared to unreinforced sand beds. For instance, at q_d/q_{ult} = 70%, in case of reinforced sand q_d = 150 kPa and q_{ult} = 214 kPa, whereas, they are 64 kPa and 91 kPa respectively for the unreinforced sand beds.

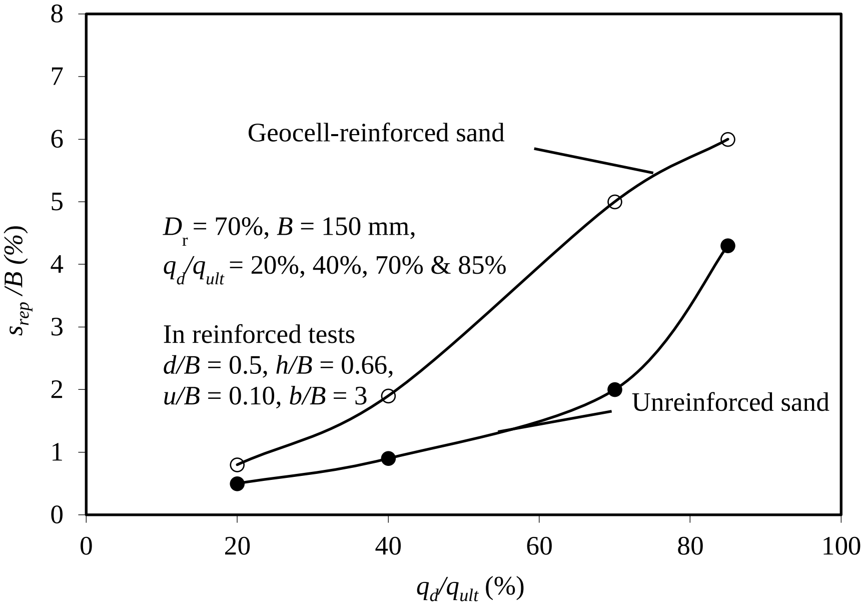


Fig. 5.5 Variation of repeated settlement, (s_{rep}/B), with repeated load ratio, (q_d/q_{ult}) after 20 load cycles

5.2.2 Effect of number of load cycles

Fig. 5.6 depicts the variation of total settlement against the number of load cycles for a square footing resting on unreinforced and geocell-reinforced sand beds. The repeated load ratio, $q_d/q_{ult,}$ is maintained at 70% for both tests. In the reinforced test, one layer of geocell made from woven geotextile with d/B = 0.50, h/B = 0.66, u/B = 0.1, and b/B = 3 is used. The figure clearly illustrates the increase of the total settlement at a gradually declining rate with the increase in the number of load cycles. Moreover, the effect is more prominent in the case of reinforced sand as compared to unreinforced sand. This may be because of the higher magnitude of repeated load in reinforced sand than the unreinforced sand. In Fig. 5.6, it can also be seen that the increase of the rate of settlement is very rapid for the first 10 cycles, and thereafter the rate is lower until the number of load cycles becomes 30 cycles. Fig. 5.7 represents the variation of cumulative or total settlement with the number of load cycles for the same initial repeated load intensity on unreinforced and geocell-reinforced sand beds. It is also observed that the cumulative settlement significantly reduced after the introduction of geocell reinforcement.

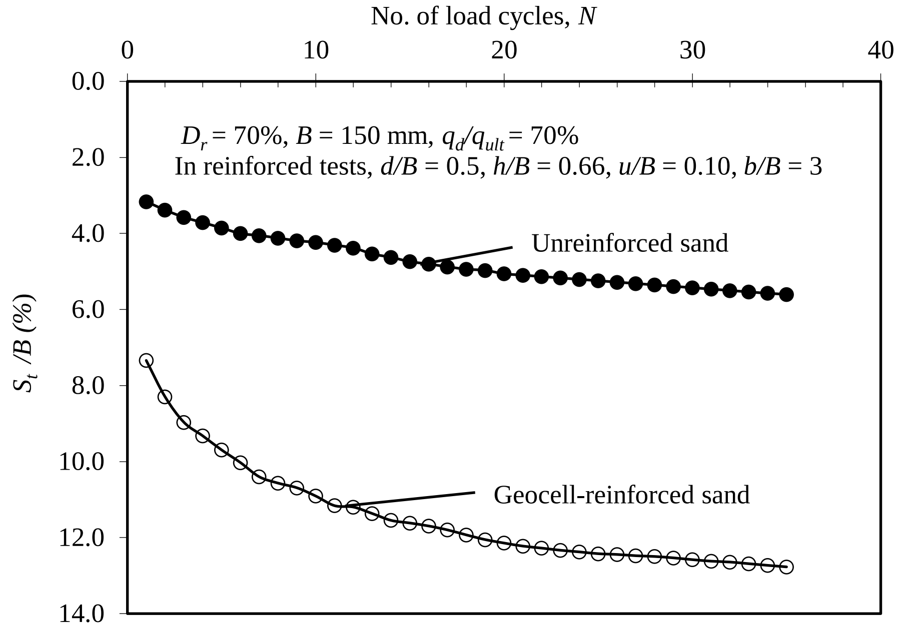


Fig. 5.6. Variation of s_t/B with N for equal q_d/q_{ult} = 70% upto 35 load cycles

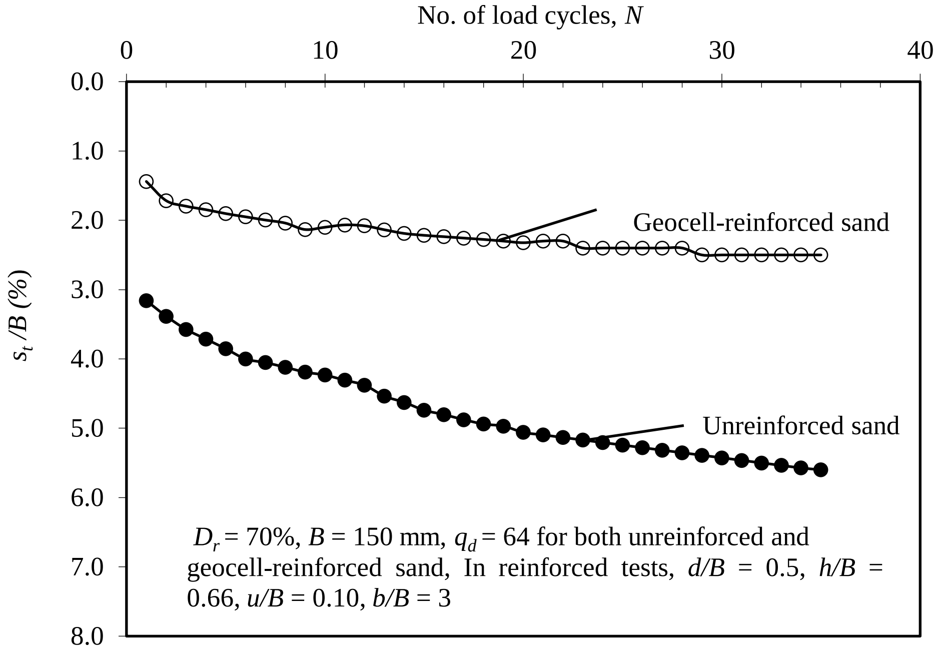


Fig. 5.7 Variation of s_t/B with N for equal repeated load intensity upto 35 load cycles

5.2.3 Effect of depth of geocell reinforcement position

Test series C2 (Table 3.4) was conducted to investigate the effect of the depth of geocell reinforcement position under repeated loading. The pressure-settlement response of unreinforced and geocell-reinforced sand beds having 70% relative density and different depths of geocell position (*u/B* = 0, 0.1, 0.25, 0.5 & 1) under repeated loads are shown in Fig. 5.8(a-e). Since the ultimate bearing capacity of the unreinforced sand bed with D_r = 70% is about 91 kPa (Chapter 4, Fig. 4.2), therefore, the unreinforced sand is not loaded beyond 91 kPa. Otherwise, the settlement increases very high even for a slight increase in load. In reinforced sand, the intensity of repeated load is kept at 91 kPa and 150 kPa except for the geocell reinforcement placed at depth *u/B* = 1 (Table 3.4). The geocell reinforcement placed at depth *u/B* = 1 is loaded 91 kPa and maximum up to 135 kPa due to the failure of reinforced sand at 135 kPa (Chapter 4, Fig. 4.17). It can be seen from the figure that the performance of geocell-reinforced sand beds under repeated load is better than the unreinforced sand bed except for the geocell reinforcement layer placed beyond *u/B* = 0.5. The figure also shows that the total settlement increases with an increase in the depth of placement of the geocell layer. Variation of total settlement of the square footing with a depth of placement of the geocell layer beneath the footing is shown in Fig 5.9. Fig. 5.10 demonstrates the percentage reduction of settlement (*PRS*) with the depth of placement of the geocell layer after 20th cycles of repetitive load. It can be seen from the figure that the cumulative settlement of the sand bed reinforced with geocell initially decreases as the depth of placement increases from *u/B* = 0 to *u/B* = 0.1, however, thereafter, the value of total settlement increases again as the *u/B* ratio increases further. The modest improvement in performance until *u/B* = 0.1 may be attributed to the confinement from a small soil cover thickness above the geocell layer promoting additional frictional resistance between the geocell and the soil. Further, as the value of *u/B* exceeds 0.25 (approaching 0.5), the geocell layer moves away from the zone where it can most efficiently interrupt the stress field and as a result, the total settlement increases. Finally, when *u/B* ratio reaches approximately one, the geocell layer is mostly outside of the significantly stressed zone (stress bulb) under the loading plate, making the reinforcing effect insignificant and the overall behaviour becomes similar to that of an unreinforced sand foundation (Fig. 5.8).

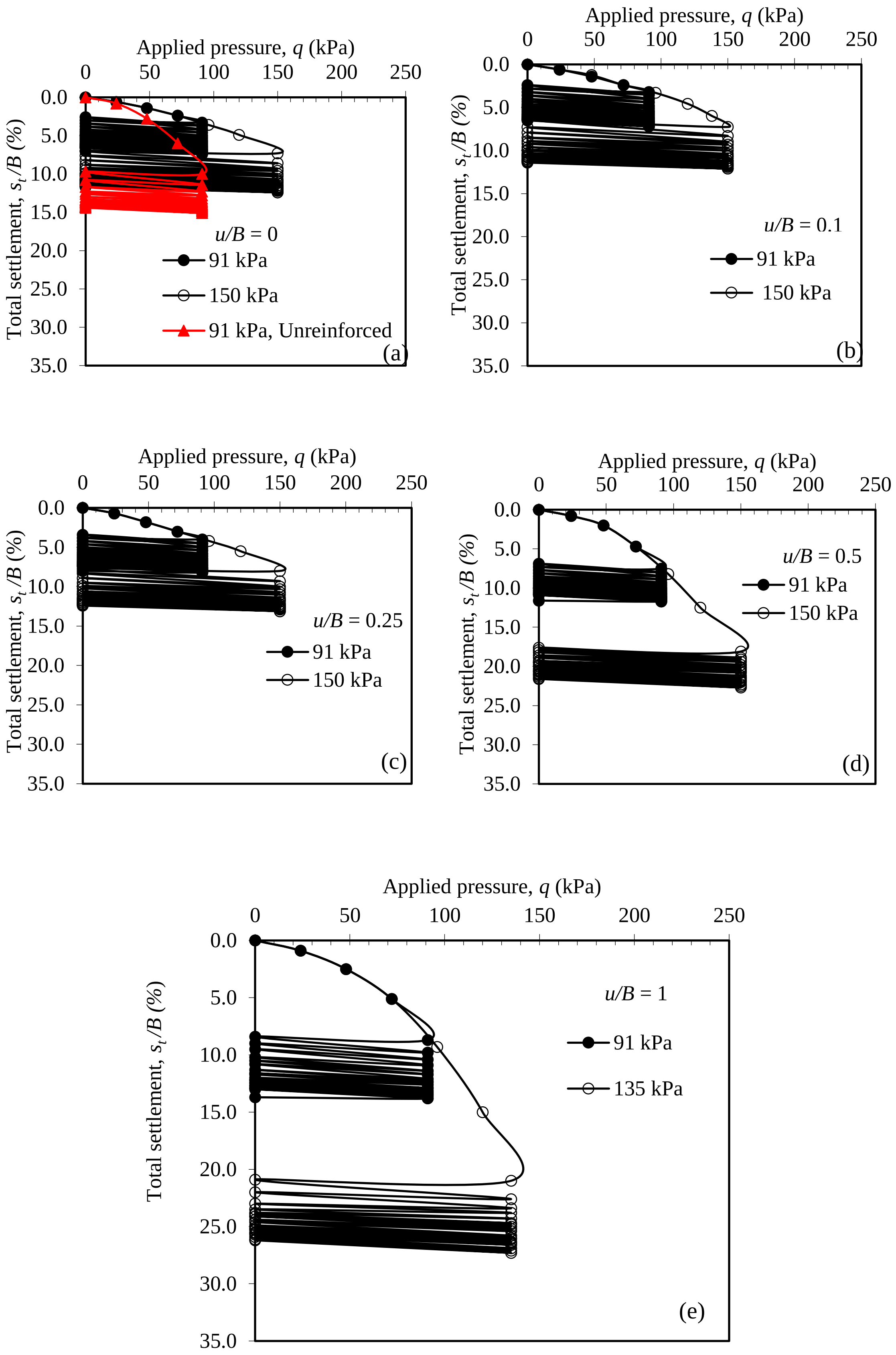


Fig. 5.8 Variation of total settlement with applied pressure for different depths of placement of geocell layer with geocell, *d/B* = 0.5, *h/B* = 0.66, *b/B* = 3 & D_r = 70%

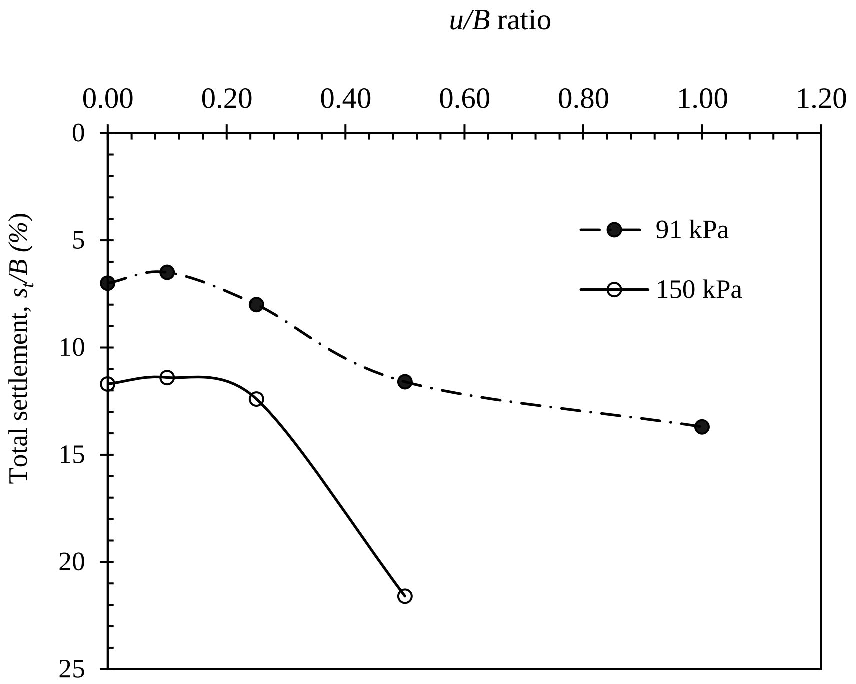


Fig. 5.9 Total settlement (s_t) vs *u/B* ratio for different repetitive load after 20th load cycles

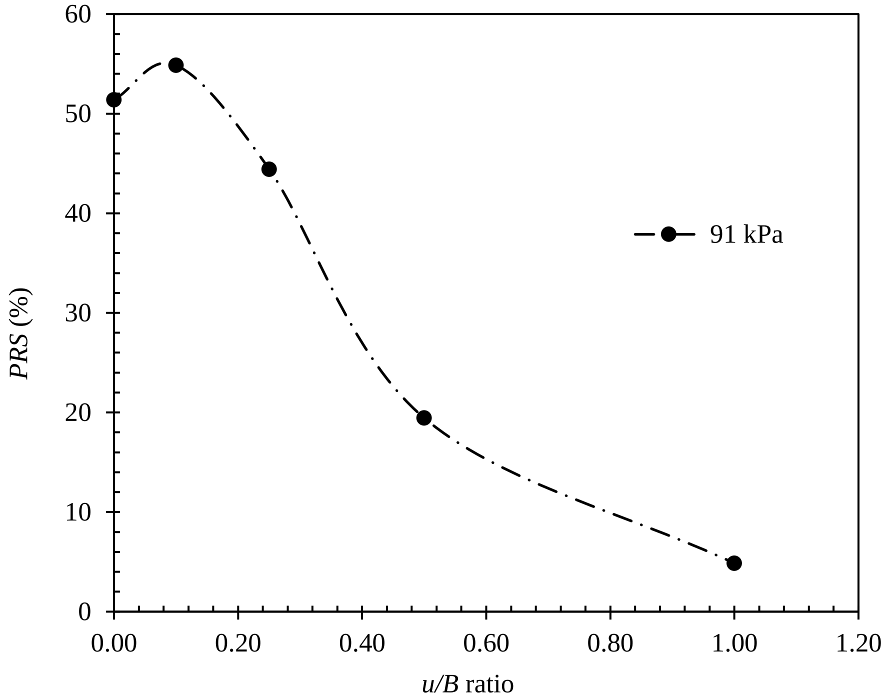
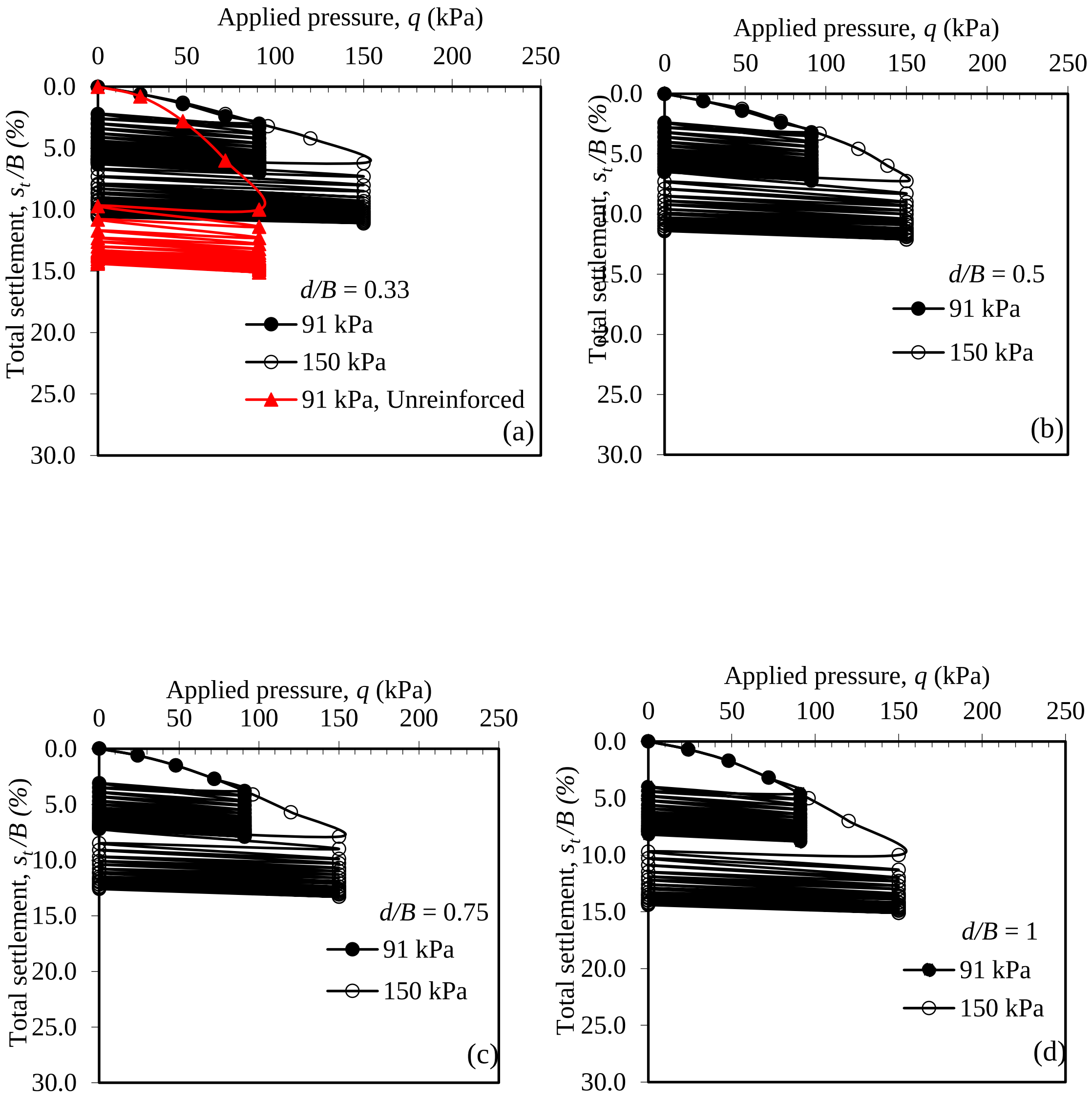


Fig. 5.10 Percentage reduction of settlement (*PRS*) vs *u/B* ratio after 20th load cycles for a repetitive load of 91 kPa

5.2.4 Effect of geocell pocket size

The variation of footing settlement with applied pressure for different values of geocell pocket size ratio (*d*/*B*) under repeated loads (from test series D2, Table 3.4) is shown in Fig. 5.11.



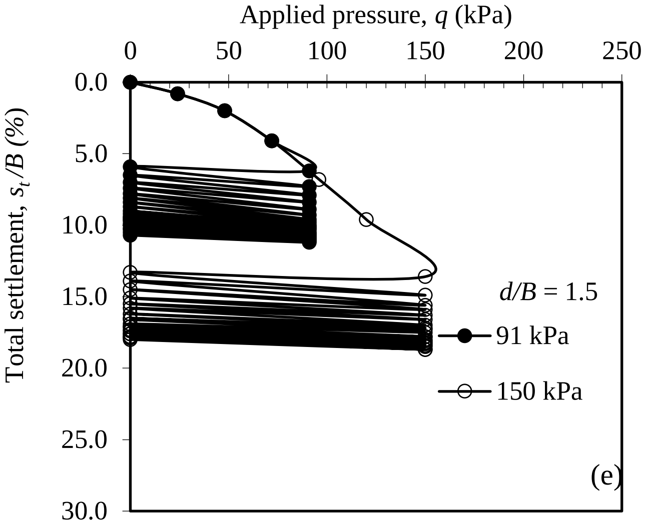


Fig. 5.11 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds with geocell with *h/B* = 0.66, *b/B* = 3, *u/B* = 0.10 & D_r = 70% for different geocell pocket sizes

Fig. 5.12 shows the variation of total settlement with geocell pocket size (*d/B*) after the 20th load cycle for different intensity of load levels. It can be seen from the figure that the total settlement increases rapidly with an increase in pocket size. For instance, after the loading stage of the 20th cycle, the total settlement (s_t/B) is about 18% for geocell pocket size (*d/B*) 1.5, whereas it is 11.4% for the *d/B* = 0.5 (Fig. 5.12).

Fig. 5.13 shows the effect of geocell pocket size on the percentage reduction of the total settlement. It is observed that the *PRS* value reduces substantially with an increase in pocket size. The *PRS* value calculated after the 20th cycle of repetitive loading is found to be about 54% for *d/B* = 0.33, whereas it is about only 23% for geocell pocket size of *d/B* = 1.5. This indicates that for better performance of geocell reinforcement under the footing, the pocket size of the geocell should preferably be not larger than the footing width.

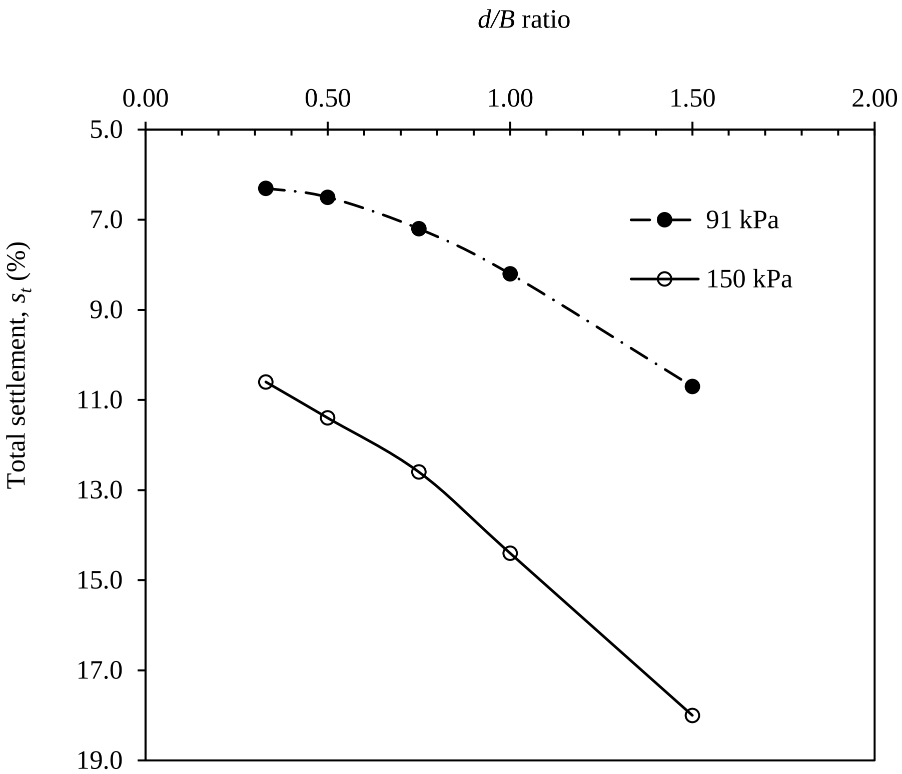


Fig. 5.12 Variation of total settlement (s_t/B) after 20th load cycles with geocell pocket size (d/B) for different intensity of load levels

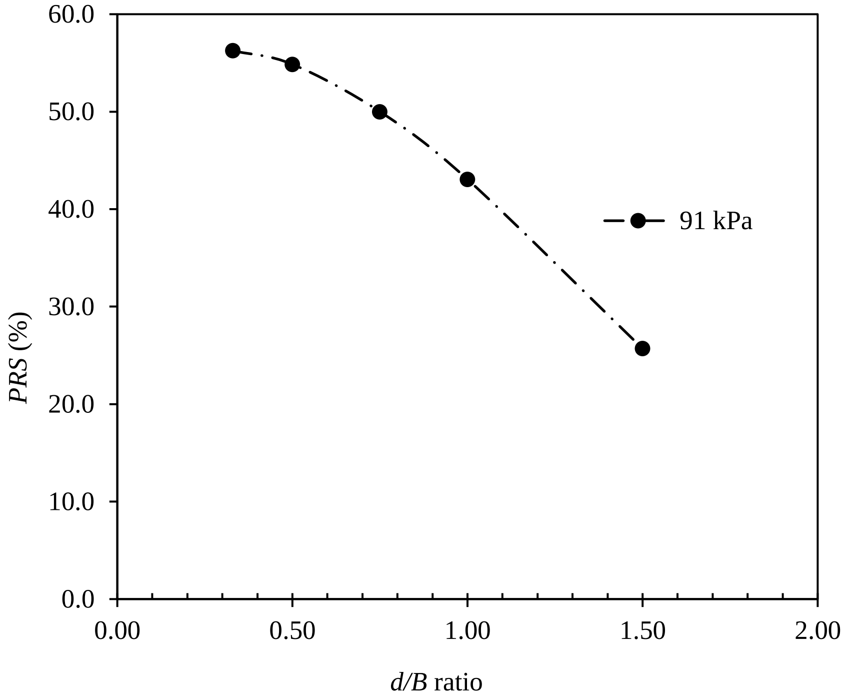
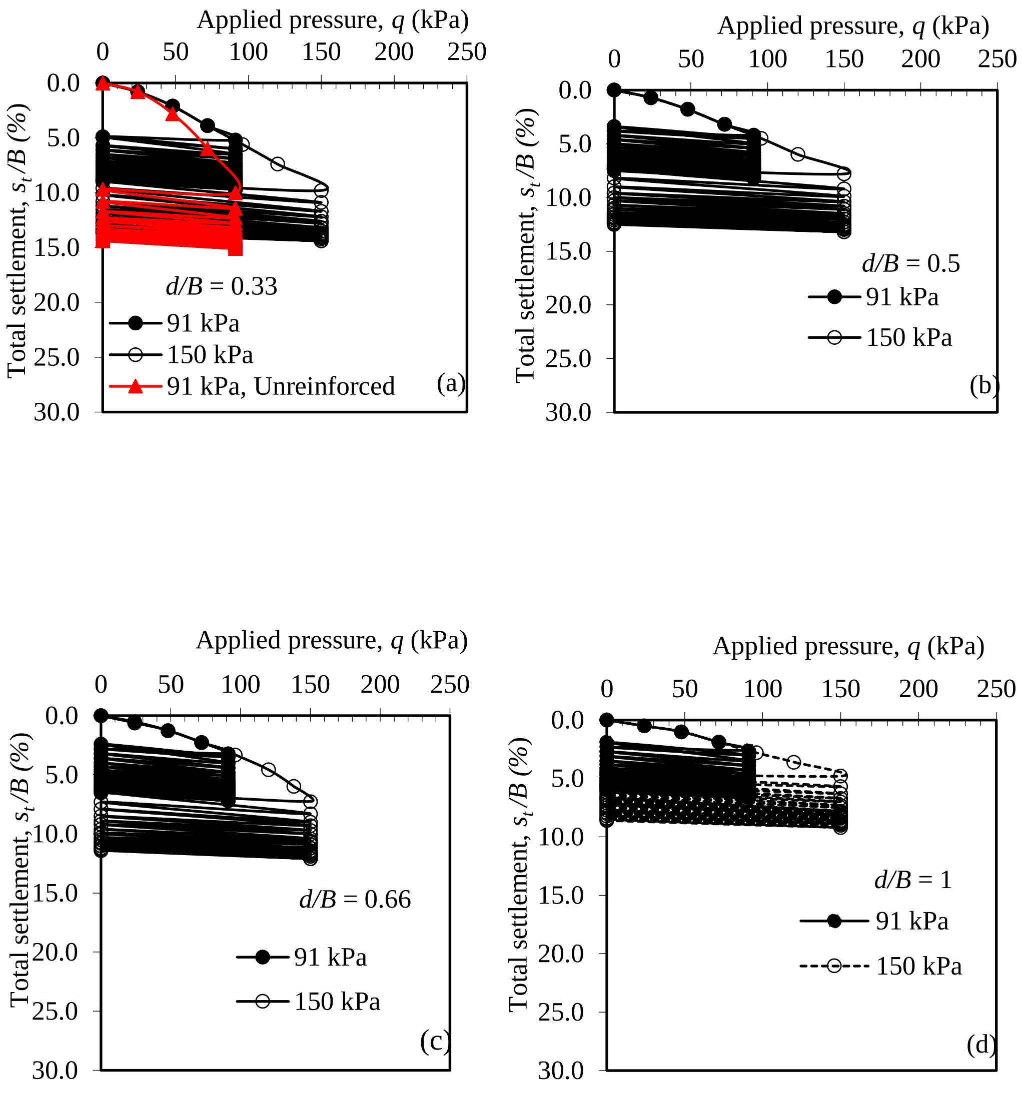


Fig. 5.13 Variation of percentage reduction of settlement (*PRS*) after 20th load cycles with geocell pocket size ratio (d/B)

5.2.5 Effect of height of geocell mattress

The results of test series E2 (Table 3.4) are shown in Fig. 5.14. Fig. 5.14 presents the variation of pressure settlement behaviour of different heights of the geocell layer. The results indicate that the total settlement of the footing is significantly reduced compared to the settlement of unreinforced sand due to an increase in height of the geocell layer (*h/B*).



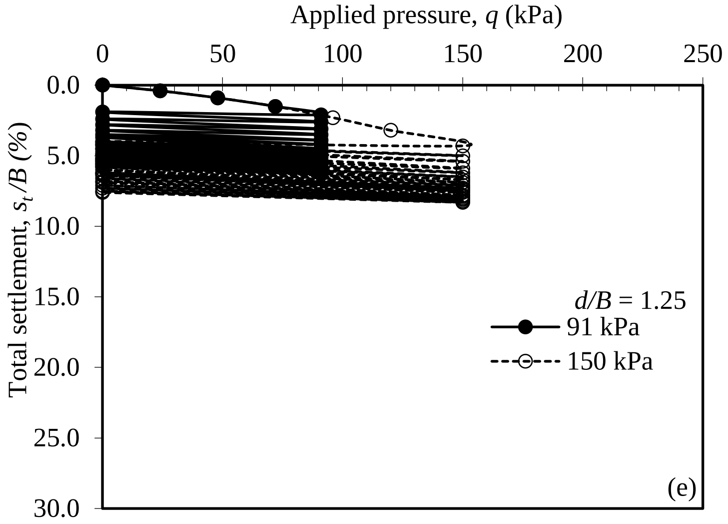


Fig. 5.14 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds (*d/B* = 0.5, *b/B* = 3, *u/B* = 0.10 & D_r = 70%) for different heights of the geocell layer

The variation of percentage reduction in total settlement (*PRS*) with the height of the geocell layer and aspect ratio (*h/d*) after the 20th load cycles is shown in Fig. 5.15. It can be seen from the figure that when the height of the geocell layer is increased from *h/*B = 0.33 to *h/B* = 1.25 the *PRS* value increases. However, the performance improvement of *PRS* value beyond *h/B* = 0.66 is marginal indicating the optimum height of the geocell. Further, the aspect ratio (height to diameter, *h/d*) for the geocell layer of 100 mm height (*h/B* = 0.66) is 1.33. Literature (Rajagopal et al., [102]) also suggests that the best aspect ratio for the maximum benefit of geocell reinforcement is between 1 and 1.67.

Fig. 5.16 illustrates the relation between the height of the geocell layer and the total settlements that occur after 20 repetitions of loadings. The figure depicts that as the height of the geocell layer increases, the total settlement decreases. This is because of increase in height of the geocell layer increases the overall frictional resistance due to the increase in surface area and as a result the resistance to the downward movement of the soil increases.

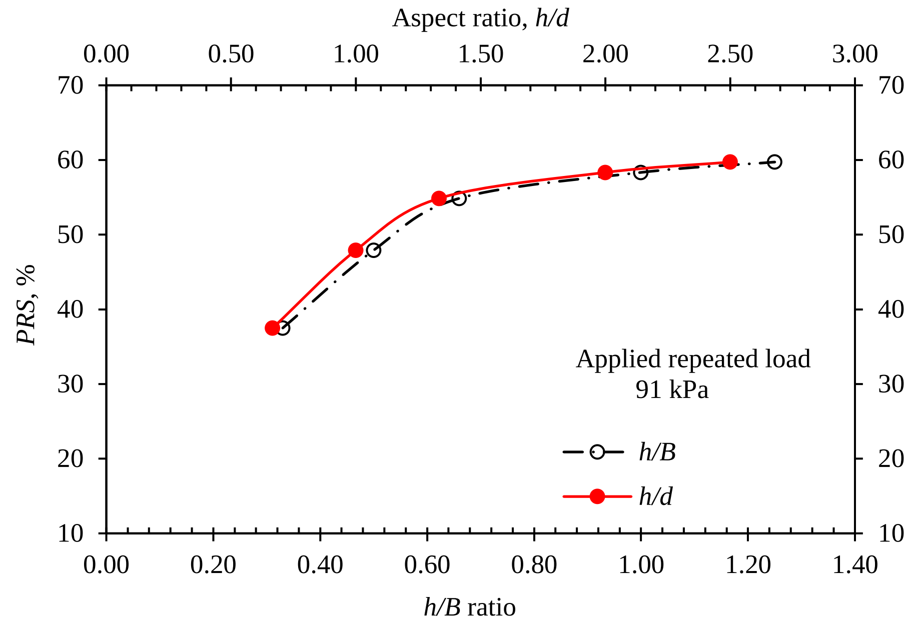


Fig. 5. 15 Variation of *PRS* versus height of geocell layer (*h/B*) and aspect ratio (*h/d*) of geocell reinforcement after 20th load cycles

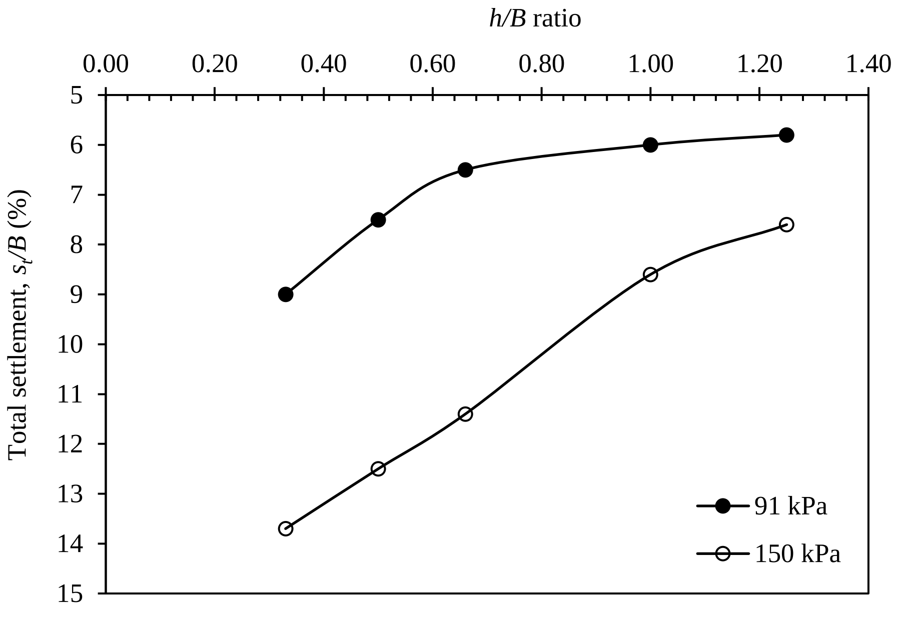
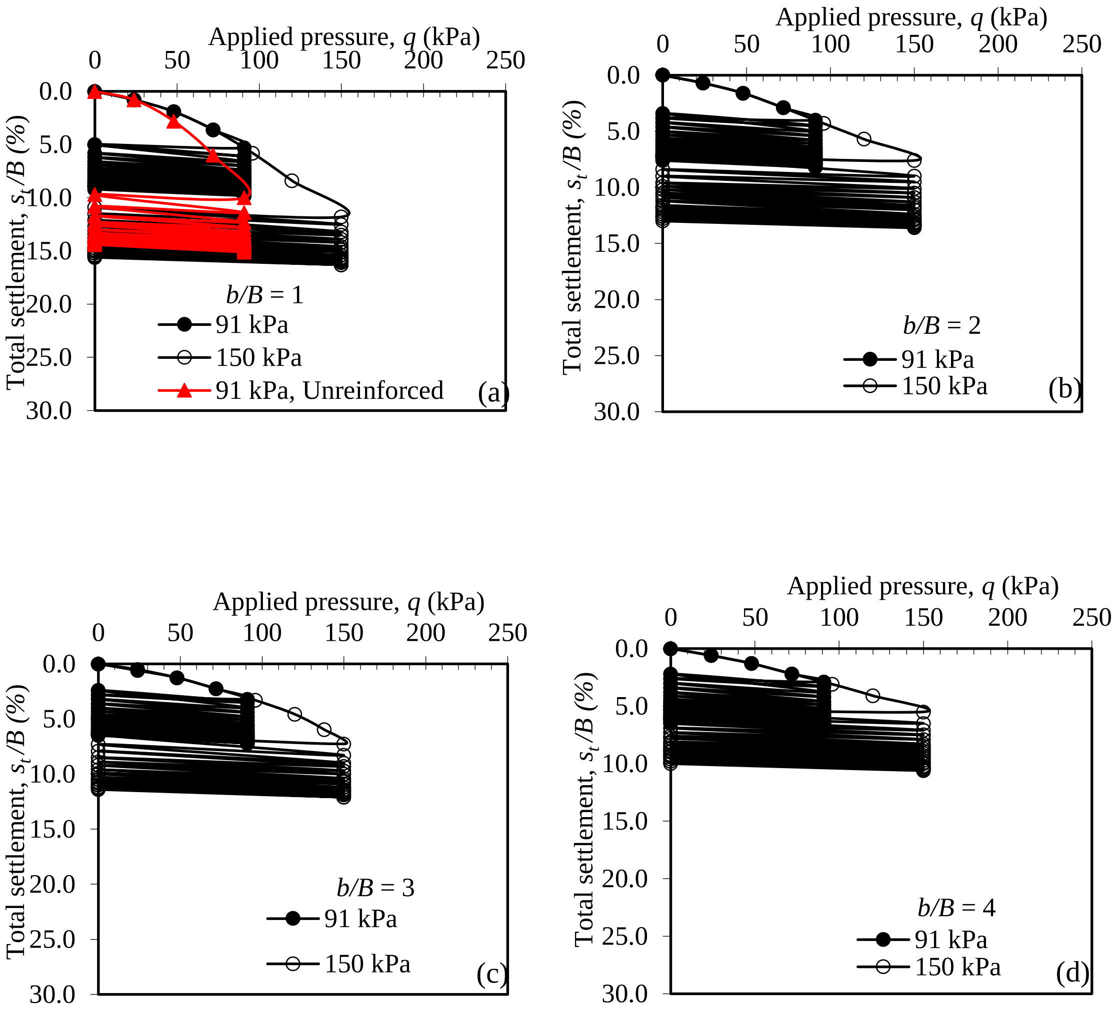


Fig. 5.16 Variation of s_t/B with *h/B* ratio at different settlement levels after 20th load cycles

5.2.6 Effect of geocell-reinforcement width

The pressure-settlement response of square footing supported on geocell-reinforced sand beds of different widths of geocell reinforcement layer (test series F2, Table 3.4) is presented in Fig. 5.17. Fig. 5.18 shows the variation of cumulative settlement with a width of geocell reinforcement (*b/B*) after the 20th load cycle for different intensity of load levels. It can be seen from the figure (Fig. 5.17) that with the increase in the width of the geocell layer, the cumulative settlement decreases. The reduction in cumulative settlement can be attributed to the increase in elastic response of geocell-reinforced sand beds with an increase in geocell width ratio. Further, it is also noted that for a magnitude of 91 kPa of repetitive load, the cumulative settlement reduces from 9.2% to 6.8% for the geocell width ratio (*b/B*) from 1 to 3 (Fig. 5.18). However, for the same magnitude of repetitive loads, the cumulative settlement reduces from 6.8% to 6.2% only for the geocell width ratio from 3 to 5 (*b/B*). This indicates that there is a marginal reduction in cumulative settlement with the geocell width ratio beyond *b/B* > 3.



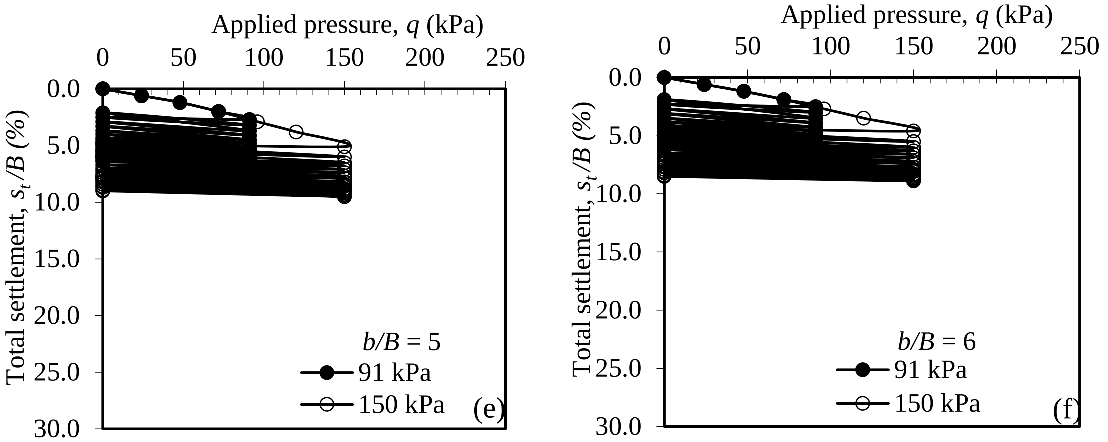


Fig. 5.17 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds with geocell, *d/B* = 0.5, *h/B* = 0.66, *u/B* = 0.10 & D_r = 70% for different widths of geocell reinforcement

Fig. 5.19 illustrates the variation of *PRS* with a width of geocell reinforcement layer normalized with footing width. The test result shows that with increases in the width of the geocell reinforcement layer, the *PRS* value increases. It can be also noted that there is a marginal increase in *PRS* value beyond *b/B* = 3.

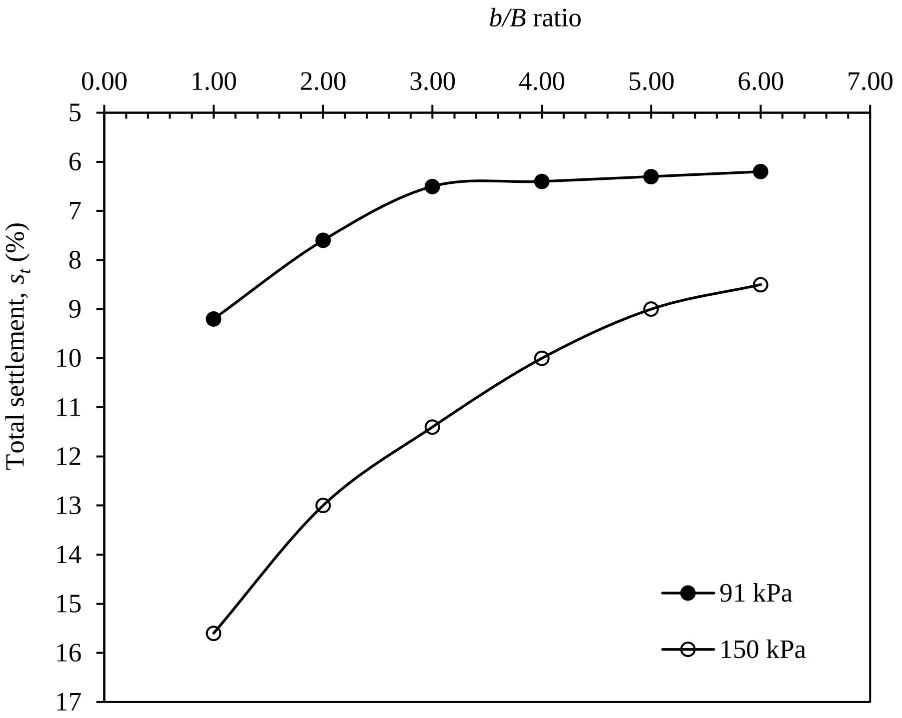


Fig. 5.18 Variation of cumulative settlement vs *b/B* ratio after 20th cycles of repeated loads

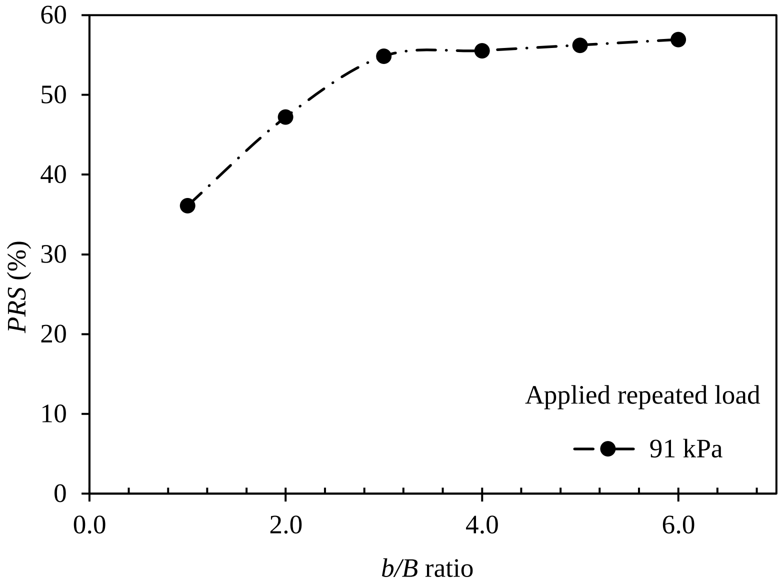


Fig. 5.19 Variation of percentage reduction of settlement (*PRS)* after 20th load cycles with geocell reinforcement width ratio (*b/B*)

5.2.7 Effect of relative density variation

In order to study the effect of the relative density of subgrade sand, six numbers of tests are conducted on model footing supported on unreinforced and geocell-reinforced sand beds set up at three-unit weights representing loose, medium, and dense relative densities (test series G2, Table 3.4). Fig. 5.20 shows the variation of total settlements with applied pressure having different relative densities (D_r = 35%, 70% & 90%) for unreinforced and geocell-reinforced sand beds. The unreinforced sand beds having relative density 35%, 70%, and 90% can bear only pressure of 58 kPa, 91 kPa, and 128 kPa, respectively, beyond which the settlements are very high even for a slight increase in load (Chapter 4, Fig. 4.7). Therefore, the unreinforced sand with D_r = 35%, 70% & 90% are not loaded beyond 58 kPa, 91 kPa, and 128 kPa, respectively. The variation of total settlement with relative density after the 20th load cycles for the different magnitudes of repeated load (91 kPa & 150 kPa) is shown in Fig 5.21. It can be seen from the figure that the benefit of reinforcement is evident only at the higher magnitude of the repeated load. For instance, after the loading stage of the 20th cycle, the total settlement (*s/B*) is about 12.2% for D_r = 35%, whereas it is only about 8.5% for D_r = 90%. This could be because, at the higher magnitude of repeated load, the reinforcement and denseness of subgrade soil take active participation as a composite material.

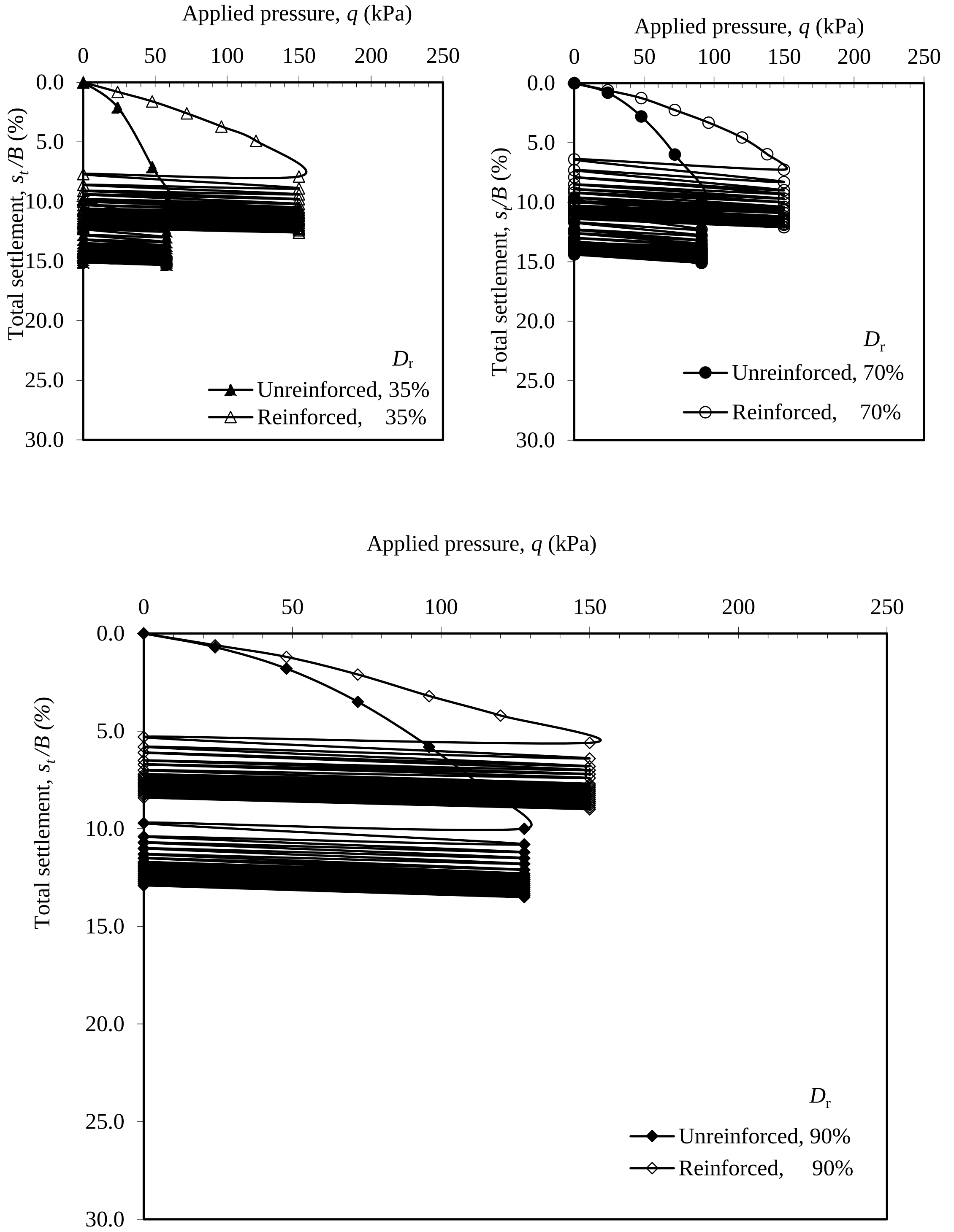


Fig. 5.20 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds (*d/B* = 0.5, *h/B* = 0.66, *b/B* = 3, *u/B* = 0.10 & D_{infill} = 70%): (a) D_r = 35%; (b) D_r = 70%; and (c) D_r = 90%

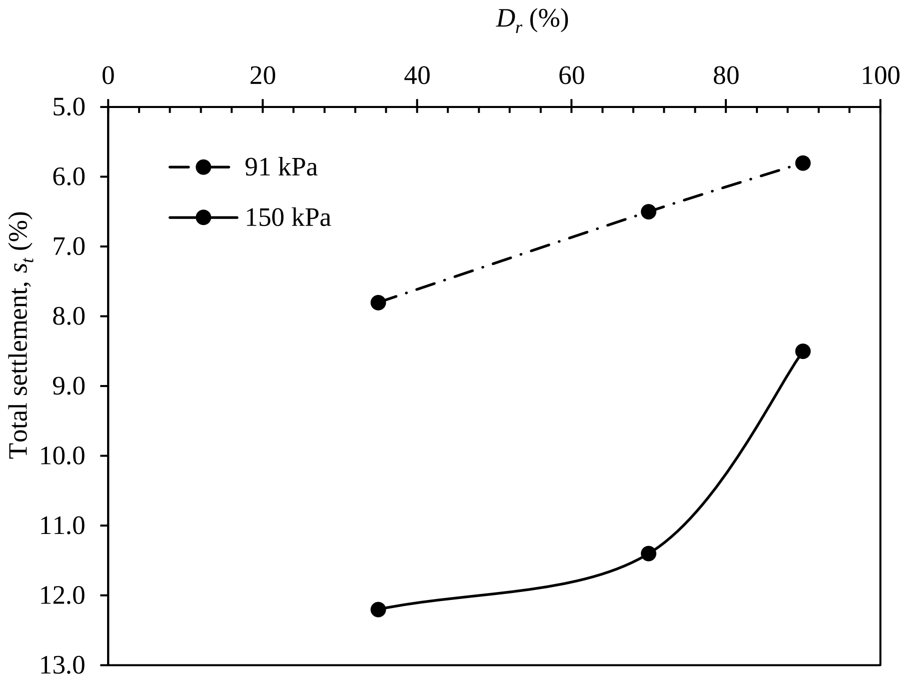


Fig. 5.21 Variation of total settlement vs relative density (D_r) after 20th load cycles for the different magnitudes of repeated load (91 kPa & 150 kPa)

5.3 Summary

The results of a series of model-scale tests conducted to investigate the behaviour of square footing under repeated loads are described in Chapter 5. Total fifty-one numbers of laboratory load tests are performed to investigate the effect of various parameters such as initial static load levels, number of load cycles, placement depth of geocell layer from the bottom of the footing, the equivalent diameter of geocell pocket, the height of geocell reinforcement layer, geocell reinforcement width and relative density of subgrade sand on the performance of square footing under repeated loads. Based on the test outcome, the following conclusions can be made:

- In circumstances where structures are highly vulnerable to large settlements, geocell reinforcement could be effectively used to attain the same allowable load-carrying capacity at a much lower settlement for the same soil density.

- For the application of the same initial static load intensity and the number of load cycles, the amount of total settlement due to repeated loading decreased with the provision of a geocell layer. It was evident that the total settlement of the sand bed with the same relative density was reduced by 56% with the inclusion of the geocell layer after the application of 20 cycles of loading.

- For the same number of load cycles, the total settlement due to repeated load increased with increasing initial static load. Therefore, for better performance of the foundation, the initial repeated load level should be kept below 30% of the ultimate bearing capacity.

- The total settlement was found to be increased with the number of load cycles at a gradually decreasing rate. For all the tests, most of the total settlement was observed to be occurred due to the first ten cycles, and thereafter, the rate became slower until the number of cycles reached 30 cycles.

- The optimum embedded depth of the geocell layer beneath the footing under repeated loads is approximately 0.1*B*.

- As the equivalent diameter of geocell pocket size increases, the cumulative settlement of the footing under repeated load increases. This happens because of increase in geocell pocket size decreases the confinement effect of soil and frictional resistance of the soil-geocell interface.

- Increasing the height of the geocell layer resulted in better performance of geocell-reinforced sand beds due to the better load spreading of the composite system. However, the beneficial effect becomes marginal after a certain height. For instance, the *PRS* value increases with an increase in *h/B* until 0.66. However, an increase in height of the geocell layer beyond *h/B* = 0.66 has little influence on the *PRS*.

- For a given value of the magnitude of repeated load, with an increase in the width of geocell reinforcement, the cumulative footing settlement decreases. However, the efficiency decreases with increases in the width of reinforcement after reaching the optimum value.

- With the increase in the relative density of the sand subgrade, the cumulative settlement decreases due to an increase in the stiffness of the foundation bed. Further, the benefit of reinforcement is more evident at a higher magnitude of repeated load due to the active participation of soil and reinforcement as a composite material.