# Static and Cyclic Behavior of Granular Piles Foundation Composed of Tire chips - Aggregates Mixture in Soft Soil

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*by*


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# CHAPTER 8

# CONCLUSIONS AND FUTURE SCOPE

## 8.1 General

Out of all available techniques for supporting large infrastructure projects such as oil storage tanks, road embankments, railways, airport runways, bridge abutments, buildings, etc., granular piles are among the best-suited techniques used worldwide. Traditionally, aggregates have been used for constructing granular piles. In some major projects, these granular piles have also been encased with either geotextile or geogrid encasements. However, natural resources have been increasingly depleted over time due to the extensive use of traditional aggregates in infrastructure projects. Hence, it is imperative to investigate alternative materials for constructing granular piles.

This study explores the use of recycled tire chips as an alternative material for aggregates in granular piles. A total of 97 laboratory scale tests were performed on granular piles installed in soft ground and subjected to static and cyclic loading. Details of scaling and physical modelling, material characterization, methodology, and the model testing procedure are comprehensively explained. Different mix proportions of tire chips and aggregates were used in granular piles.

When granular pile foundations installed in very soft soil beds are loaded through the supporting structure, the piles bulge due to insufficient lateral support provided by the surrounding soil, leading to large settlements and potential structure failure. To overcome this drawback, granular piles are strengthened by providing geosynthetic encasements in the form of vertical encasements, horizontal discs, or combined encasements. This study used combi-grid, geotextile, and geogrid as encasement

materials for granular piles. The model test results are also validated using finite element analyses with PLAXIS 3D. The major conclusions from all the chapters are summarized below.

## 8.2 Engineering properties of tire chips - aggregates mixtures

- The dry unit weight and specific gravity values of the aggregate and tire chips mixture decreased with increasing tire chip content. The reduction in the dry unit weight of the mixture from 0% tire chips to 25% tire chips by volume is 14.60%, primarily due to the low specific gravity of tire chips. This finding indicates that the aggregates and tire chips mixture effectively serve as a lightweight backfill material for geotechnical structures.
- Based on the void ratio and shear strength of the aggregates and tire chips mixture, the optimum tire chip content is 25% by weight, equivalent to 44.40% by volume. The percentage decrease in the void ratio of the mixture from 100% aggregates to 25% tire chips content is 31.8%. This can reduce the need for large amounts of aggregates in various ground engineering applications. This optimum mixture offers better compressibility due to a lower void ratio and higher bearing capacity due to greater shear strength.
- At normal stress of 50 kPa, the shear strength of the aggregate and tire chips mixture decreases with increasing tire chip content. The percentage reduction in shear strength from 100% aggregates to a mixture with 25% tire chips by weight is 4.6%.
- At 70% relative density, the angle of internal friction values of the mixture decreases with increasing percentages of tire chips. The angle of internal friction ($\phi$) for 100% aggregates is 40.11°, while for (25% TC + 75% AG), it is

37.22°. The decrease in $\phi$ value is approximately 3° with the addition of 25% tire chips by weight.

- At 70% relative density, the cohesion values of the mixture increase with an increasing percentage of tire chips. The cohesion ($c$) for 100% aggregates is 0 kPa, and for (25% TC + 75% AG), it is 3.10 kPa. The increase in $c$ value is 3.10 kPa with the addition of 25% tire chips by weight.
- Based on the vertical deformation and shear strain curves, the mixture's maximum dilation angle ($\psi$) decreases with the increment of tire chips. Up to 25% tire chip content, initial compression is negligible, and the mixture mainly dilates upon shearing.
- The improvement factor ($F_{mp}$) of the granular pile composed of aggregates and tire chips mixture with 25% tire chips is 0.88 times that of 100% aggregates. Thus, the improvement loss for 25% tire chip content is 12%, which is minimal and positively impacts environmental and sustainable infrastructure.
- The secant shear modulus of the tire chips and aggregates mixture is reduced by adding tire chips at constant normal stress. Including tire chips makes the mixture more ductile, thereby decreasing its shear stiffness.

## 8.3 Static model tests on single granular piles

- The efficiency of ordinary granular piles made of (0% TC + 100% AG) and (25% TC + 75% AG) is nearly 100%. Therefore, the optimum mix proportion of tire chip content replacing aggregates is 25%, without compromising load-bearing capacity and allowing effective utilization of waste tire chips.
- The combi-grid encasement can substantially increase the load-carrying capacity over OGP and soil bed alone. The ultimate bearing capacity of VEGP with (25% TC + 75% AG) is 2.20 times that of OGP with (0% TC + 100%

AG). The efficiency of a combi-grid encased granular pile is more than 1 for all mix proportions of tire chips and aggregates.

- The ultimate bearing capacity of the granular pile with horizontal discs increases as the vertical spacing between horizontal discs decreases. The ultimate bearing capacity of granular piles encased with horizontal discs at a spacing of 0.25D is 1.44 times that of VEGP.
- The best configuration is the granular pile encased with combined encasement with a spacing of 0.25D for the full length. The ultimate bearing capacity of CEGP with a spacing of 0.25D is 1.76 times that of VEGP and 1.22 times that of HEGP with 0.25D spacing.
- The ultimate load intensity ratio ($\beta$) of VEGP, HEGP with a spacing of 0.25D, and CEGP with a spacing of 0.25D is observed to be much higher, in the range of 3.33, 4.81, and 5.85, respectively. For field applications, in the case of CEGP, the number of granular piles can be significantly reduced compared to unreinforced and fully encased granular pile-supported structures.

## 8.4 Cyclic model tests on single granular piles

- The maximum cyclic induced settlement ($S_c$) of the ordinary granular pile (OGP) with (0% TC + 100% AG) and (25% TC + 75% AG) are 30 mm and 34.8 mm, respectively. This results in a percentage efficiency reduction of nearly 12% for 25% tire content, indicating a relatively minor decrease. However, the substitution of aggregates with 25% tire chips offers a positive impact on sustainable infrastructure development.
- The provision of combi-grid encasement to the granular pile with (25% TC + 75% AG) resulted in a substantial reduction in cyclic-induced settlement ($S_c$) by approximately 4.50 times greater than OGP with (0% TC + 100% AG).

This finding emphasizes the superior performance of combi-grid as the most advantageous encasement for granular piles subjected to cyclic loading.

- The maximum excess pore water pressure ($P_{exc}$) of soil bed, OGP, and CGGP with (25% TC + 75% AG) is 27.2 kPa, 18.7 kPa, and 8.9 kPa, respectively. This demonstrates a significant reduction in the ($P_{exc}$) of the improved soil bed with the installation of OGP, representing a reduction of 31.3%. Moreover, CGGP exhibits a remarkable decrease of 67.2% in ($P_{exc}$), highlighting its effectiveness in mitigating excess pore water pressure accumulation.

## 8.5 Effect of principle parameters on single granular piles under cyclic loading

- The provision of encasements to granular piles in the form of GT, GG, and CG resulted in significant reductions in granular pile settlement, with reductions of 63%, 72%, and 81%, respectively, compared to the OGP. These findings conclude that the combi-grid, a hybrid composite incorporating geotextile and geogrid components, demonstrates superior effectiveness in reducing cyclic-induced settlement ($S_c$) compared to encasements comprised solely of geotextile or geogrid materials.
- The performance of ordinary granular piles in enhancing the cyclic capacity of soft soil beds is notable under specific conditions, such as lower cyclic loading frequencies ($f_{cy}$), reduced cyclic amplitudes ($q_{cy}$), higher length-to-diameter ($L/D$) ratios, and end-bearing conditions. Conversely, applying combi-grid encasement to granular piles shows distinct improvements across more challenging circumstances, including higher cyclic loading frequencies, increased cyclic amplitudes, lower $L/D$ ratios, weaker surrounding soil conditions, and various granular pile end conditions. The consistent reduction

in cyclic-induced settlement ($S_c$) in improved soft beds underscores the effectiveness of combi-grid encasement, regardless of the diverse factors analyzed.

- A notable difference in excess pore water pressure dissipation ($P_{exc}$) between OGP and VEGP emerges across all examined cyclic factors. Specifically, OGP develops nearly twice the $P_{exc}$ compared to VEGP. This phenomenon remains consistent regardless of variations in cyclic factors such as frequency ($f_{cy}$), cyclic amplitude ($q_{cy}$), length-to-diameter ratio ($L/D$), the strength of the surrounding soil bed ($S_u$), and granular pile end conditions.

## 8.6 Static and cyclic model tests on a group of granular piles

- Under static loading conditions, the ultimate load intensity ($q_{us}$)significantly increases with the installation of ordinary granular piles (OGPs), showing a percentage increment of 58%. Furthermore, combi-grid encasement leads to a substantial enhancement of 335% compared to only soil bed, highlighting the effectiveness of combi-grid as a highly efficient encasement material for granular piles subjected to static loading.
- Under cyclic loading conditions, applying GT, GG, and CG encasements reduced cyclic-induced settlements ($S_c$) for the group of granular piles by approximately 34%, 43%, and 56%, respectively, compared to OGP. This phenomenon highlights the superiority of combi-grid as the most beneficial material for granular piles subjected to cyclic loading.
- The group of OGPs excels at mitigating settlements at lower cyclic amplitudes (up to a CSR of 0.65). In comparison, combi-grid encasement proves highly effective at higher cyclic amplitudes (beyond a CSR > 0.65).This highlights OGPs effectiveness in mitigating moderate settlements, while a combi-grid

significantly benefits soft soil foundations subjected to excessive settlements due to higher cyclic amplitudes.

- In the case of a group of OGPs, cyclic-induced settlements ($S_c$) increased with higher cyclic loading frequencies ($f_{cy}$). However, the provision of combi-grid encasement resulted in smaller cyclic loading-induced settlements and larger cyclic loading capacities, regardless of the cyclic loading frequency.
- There is a notable difference in excess pore water pressure dissipation ($P_{exc}$) between groups of OGPs and CGGPs, evident in both static and cyclic loading conditions. The group of OGPs consistently exhibits nearly double the $P_{exc}$ compared to VEGPs, irrespective of variations in considered cyclic factors such as frequency ($f_{cy}$) and cyclic amplitude ($q_{cy}$).
- The group of granular piles, including OGPs and CGGPs, exhibited higher stress concentration ratios ($n$) at lower cyclic amplitudes and frequencies than higher values.

## 8.7 Plaxis 3D validations

- Irrespective of OGP or VEGP, the granular piles composed of (0% TC + 100% AG) are subjected to maximum bulging, and (100% TC + 0% AG) are subjected to minimum bulging.
- In the case of OGP, irrespective of mix proportion, the predominant bulging was observed up to 2D from the top of the granular pile.
- In the case of VEGP, the bulging was observed throughout the length of the granular pile, but bulging is significantly reduced compared to OGP due to the provision of the combi-grid encasement.

- In the case of horizontal encased granular piles (HEGP) and combined encased granular piles (CEGP), the bulging pattern was nearly following the VEGP pattern.

## 8.8 Limitations and Future Scope

- Recycled tire chips of size 10 mm × 10 mm × 10 mm and aggregates ranging from 10 mm to 12.5 mm were considered for comparison. However, the study did not account for tire chips and aggregates' size, shape, and orientation effects. This aspect presents an opportunity for further research exploration.
- The present study did not conduct field tests on granular piles comprising of aggregates and tire chips in various mix proportions. These tests would have provided valuable insights into the challenges associated with compacting the tire chips - aggregates mixture inside the granular pile and allowed for comparing performance between laboratory and field results.
- This study does not explore the potential for leachate formation from using tire chips in granular piles for soft soil improvement, which is an important environmental consideration.
- Using strain gauges at the interface between the granular pile and the surrounding soft soil to measure bulging behavior might have been insightful; however, this instrumentation was not used in the laboratory model test setup.
- Drained and undrained 3D finite element analyses under static and cyclic loading conditions may be investigated.