

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter mainly provides an overview of ground improvement using granular piles. Section 2.2 provides basic information about granular piles, which includes the working of granular piles, different construction methods, failure mechanisms, and basic relationships. Section 2.3 discusses the past literature studies on the behavior of granular piles subjected to static loadings, including experimental and numerical studies, and section 2.4 discusses the behavior of granular piles subjected to cyclic loading through experimental studies. Section 2.5 illustrates various literature studies related to recycled tire materials in civil engineering applications, followed by Section 2.6, which briefly describes the concluding remarks of this study.

2.2 Basic information

2.2.1 Working of granular pile

The enhancement of soft soil foundations through the inclusion of granular piles is attributed to three factors:

- **Reinforcement:** Incorporating stiffer granular pile materials (such as crushed stones, aggregates, and others) into the soft ground.
- **Densification:** Densifying the surrounding soft soil bed by including granular piles.
- **Drainage:** Serving as vertical drains to facilitate rapid consolidation of the subsoil under applied loading.

The axial load-bearing capacity of granular piles is attributed to the passive earth pressure generated by the bulging effect of the piles. The resistance to the bulging of

granular piles depends on the surrounding soil's frictional properties. When granular piles are installed in very soft soils, the lateral support from the surrounding soil is minimal, leading to a low load capacity. Consequently, the piles deform excessively due to bulging. Additionally, the surrounding soft soil gets squeezed into the voids of the granular materials, reducing the bearing capacity of the piles by lubricating the granular material. This process also decreases the permeability of the granular pile, hindering the rapid dissipation of excess pore water pressure.

2.2.2 Granular pile construction methods

The careful selection of an appropriate granular pile construction method and the precise on-site execution are the paramount concerns for improving soft and very soft soils. Certainly, the construction of granular piles typically follows a procedure that begins with excavating a hole in the site. This hole is subsequently filled with granular material and is compacted for required strength. The choice of granular material to fill the hole depends on the specific engineering requirements and site conditions. Different methods for constructing granular piles have been followed globally based on proven effectiveness and equipment availability in specific locations. The major installation methods are discussed below.

2.2.2.1 Non-displacement method

In this process, prior to the installation of the granular pile, the soil is taken out during boring. The removed soil is replaced by granular material and compacted. In this method, the surrounding soil is not displaced during the installation of the granular pile. Hence, there is no densification of the surrounding soil. The non-displacement technique is primarily adopted for sensitive soils. The most widely adopted non-displacement method is the rammed granular pile system.

Rammed granular pile system:

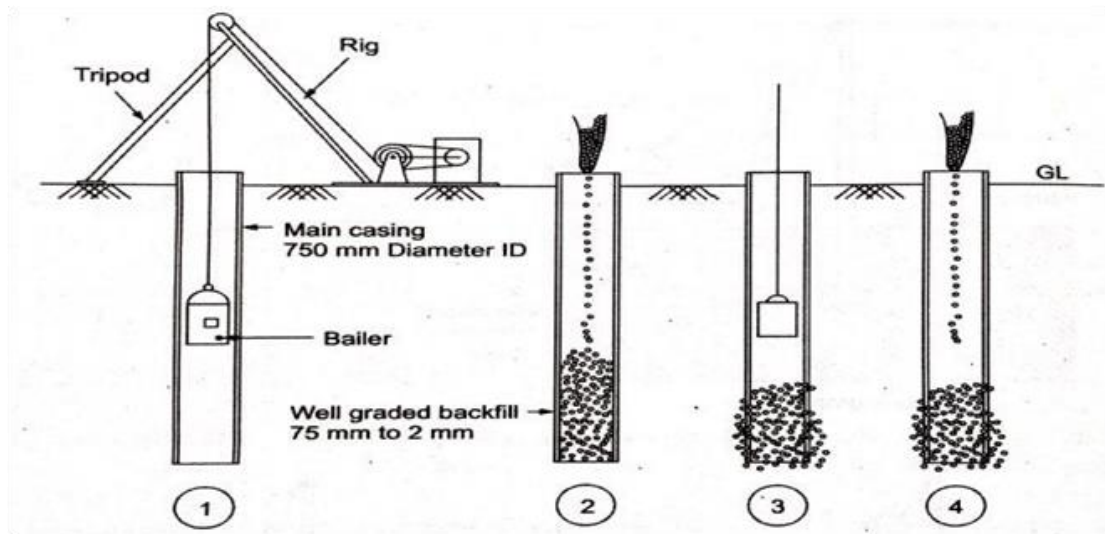


Fig. 2.1 Installation of granular pile by rammed granular pile method (Reference: Datye and Nagaraju 1975).

The rammed granular pile was proposed by (Datye and Nagaraju 1975) and was developed by (Nayak 1982). This method is also known as the cased borehole method. It is widely adopted in cohesive soils. In this technique, the soil is bored by a piling rig using a casing pipe. The casing pipe protects the sides of the borehole and minimizes disturbance to the surrounding soil. The soil is removed from the casing pipe using a bailer. The granular materials are laid into the bore and rammed to a larger diameter as the casing pipe is withdrawn. The granular piles are constructed by ramming granular materials in the pre-bored holes in stages using heavy falling weight, usually 15–20 kN from a height of 1.0–1.5 m (Datye and Nagaraju 1975). These piles achieve their strength through the lateral restraint the surrounding soil offers. Therefore, constructing the granular pile must not reduce the surrounding soil's shear strength. Hence, the rammed granular pile technique could be adopted in clays of low sensitivity. Fig. 2.1 shows the installation of a granular pile by the rammed granular pile method.

2.2.2.2 Displacement method

In this technique, the soil is laterally displaced while making the borehole install a granular pile. A vibratory probe advances the borehole, and granular fill material is introduced and compacted. The soil surrounding the granular pile is densified in this process. Vibro replacement and vibro displacement are the most widely used methods for granular pile installation.

2.2.2.2.1 Vibro replacement method

Wet top feed method

This method improves cohesive soils with a fines content of above 20% and undrained shear strength (S_u) of the soil in the range of 15 to 35 kPa. In the wet process, a hole is formed in the ground by jetting a vibrofloat down to the desired depth with water. Once the desired depth of the hole is formed, the backfilling process is typically executed with a continuous upward flow of water, allowing granular material to settle and compact effectively. This method is employed for deep ground improvement below the water table (Moseley, M.P., & Kirsch 2004; McCabe et al. 2009). This ground improvement method has proven effectiveness within a treatment depth ranging from 5 to 15 meters. In this system, it is desirable to construct end-bearing granular piles (Barksdale and Bachus 1983). Fig. 2.2 presents the schematic procedure of the wet top feed method in the field. As granular material accumulates at the bottom of the pile, the vibrator is gradually withdrawn at intervals of around 0.5 meters throughout the installation procedure. As the vibrator is gradually withdrawn in intervals, the water flow helps maintain the borehole walls' stability. This prevents the surrounding soil from collapsing into the borehole and ensures that the granular material is effectively placed and compacted within the pile.

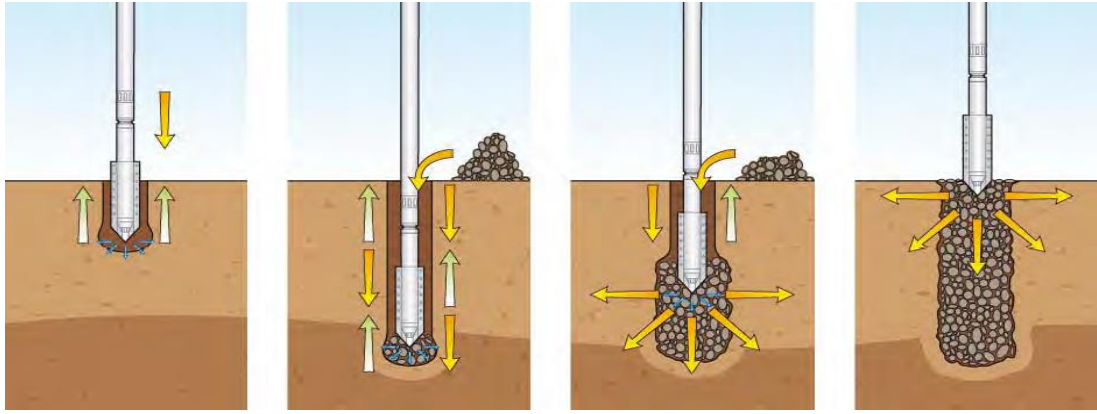


Fig. 2.2 Wet top feed method (Reference: Mokhtari and Kalantar 2012).

The major limitation of this method is the necessity for a large volume of water, which poses challenges in terms of resource usage and environmental impact. Additionally, the water used in the process must be properly managed and disposed of without causing pollution.

2.2.2.2.2 Vibro displacement method (dry method)

Dry top feed method:

This method suits stable, stiff soils with undrained shear strength greater than 30 kPa. The dry top-feed method for installing granular piles involves introducing granular material into the borehole from the top without requiring continuous water flow. This method is often preferred for its simplicity, especially in cases where treatment depths are shallow to medium. A similar procedure to the wet top-feed method is followed for installation. This method is advantageous when water use is not preferred or feasible. It reduces the environmental impact associated with water consumption and disposal.

The major limitation of the dry top-feed method is that it may not be suitable for treating soft clay soils due to the inherent risk of borehole collapse when the vibrating poker or probe is withdrawn. Soft clay soils lack sufficient lateral support, and without

the continuous presence of the vibrating tool, the borehole walls may collapse, leading to an ineffective installation of granular piles (McKelvey et al. 2004; McCabe et al. 2009). The usual geometries of constructed granular piles are typically 0.4 to 0.8 m in diameter and 10 to 15 meters in length (McKelvey et al. 2004). Fig. 2.3 illustrates the schematic procedure of the dry top-feed method in the field.

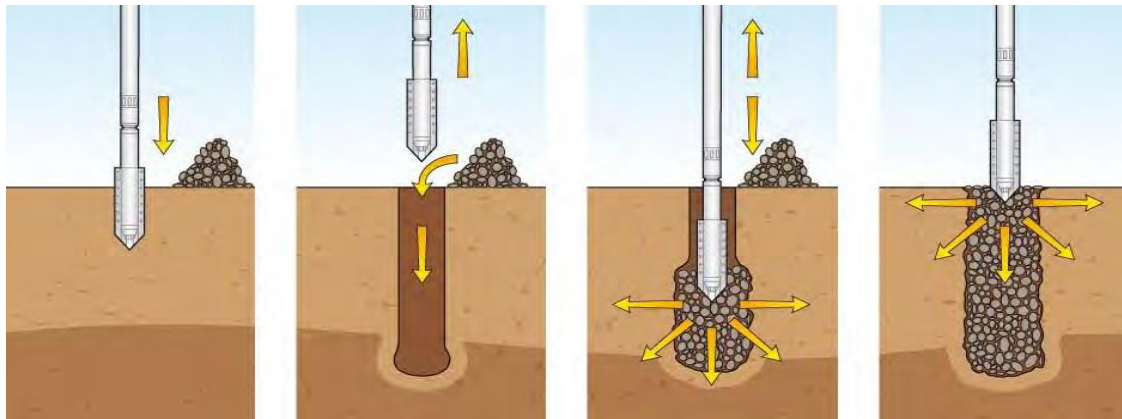


Fig. 2.3 Dry top feed method (Reference: Mokhtari and Kalantar 2012).

Dry bottom feed method:

The dry bottom-feed method was first introduced in the United Kingdom in the 1980s and is currently acknowledged as the predominant and widely adopted approach for installing granular piles (McCabe et al. 2009). This technique suits very soft soils with S_u from 15 to 50 kPa. This method introduces granular material into the borehole from the bottom without requiring a continuous water flow. The dry bottom-feed method is often employed in situations where water usage is a concern, and it provides an alternative to the wet method that involves continuous water flow during installation.

While backfilling, the vibrofloat remains within the bore, offering increased stability and preventing the unwanted inclusion of materials. This ensures a more controlled and efficient ground improvement process. A hopper is used to provide the

granular material to a tube that is attached to the vibrofloat. The usual geometries of constructed granular piles are typically 0.4 to 0.8 m in diameter and up to 15 meters long (McKelvey et al. 2004). Fig. 2.4 represents the schematic procedure of the dry bottom-feed method in the field.

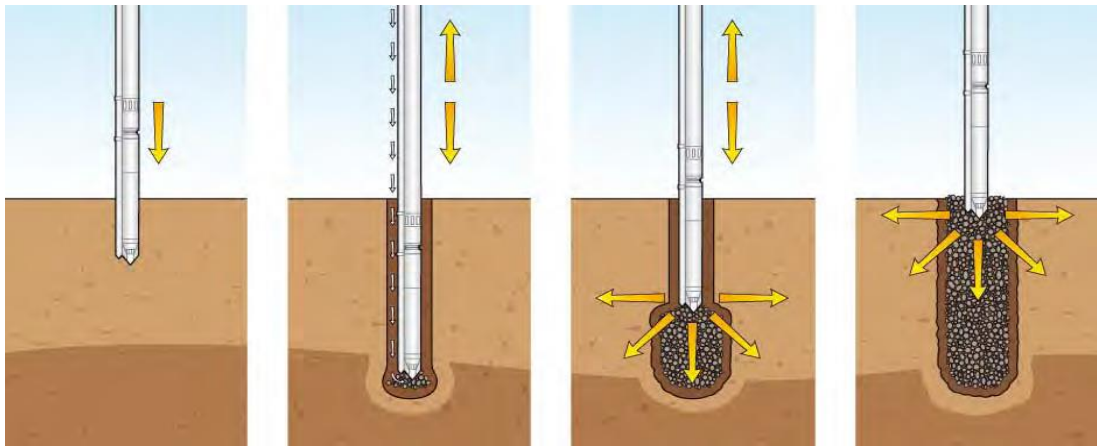


Fig. 2.4 Dry bottom feed method (Reference: Mokhtari and Kalantar 2012).

2.2.3 Granular pile failure mechanisms

Granular piles can be installed in two ways: end bearing, which rests on a hard stratum beneath soft soil, or floating, with the granular pile's tip embedded within the soft soil. According to (Barksdale and Bachus 1983; IS 15284 (part 1) 2003), the failure mode of a single granular pile loaded over its plan area is greatly influenced by the length of the granular pile. Granular piles longer than their critical length (approximately four times the pile diameter) tend to fail by bulging, regardless of whether end-bearing or floating (Fig. 2.5a). Nevertheless, piles shorter than the critical length are prone to fail due to general shear if they are end-bearing with a rigid base (Fig. 2.5b) and due to punching if they are floating (Fig. 2.5c).

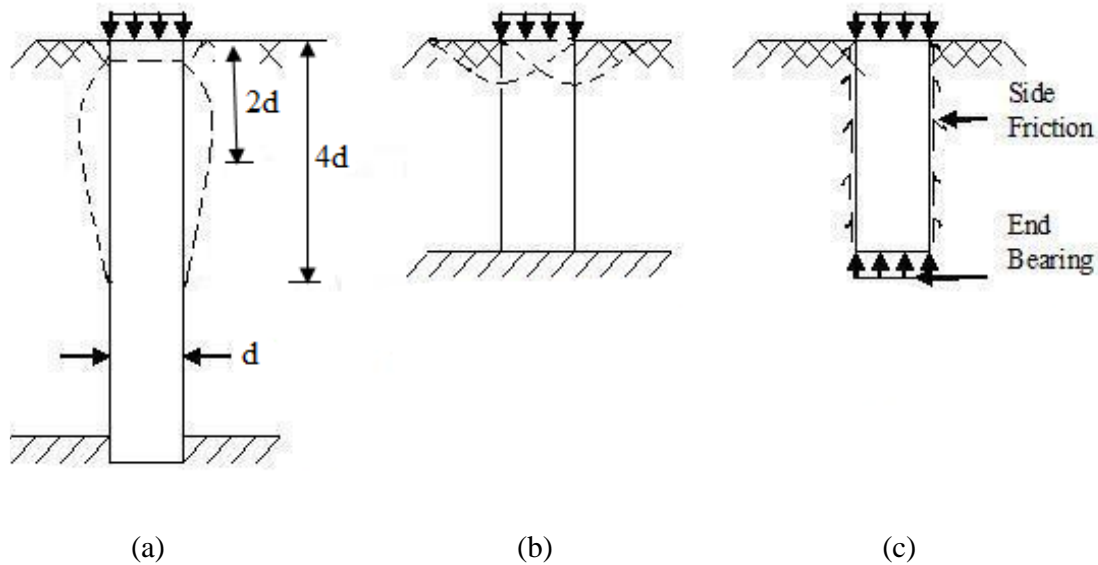


Fig. 2.5 Failure mechanisms of a single granular pile in a homogeneous soft layer according to (Barksdale and Bachus 1983; IS:15284 (Part 1) 2003), (a) Long granular pile with end-bearing or floating support-Bulging failure (b) Short granular pile with rigid base-Shear failure, (c) Short floating granular pile- Punching failure.

The above-mentioned failure mechanisms are relevant for granular piles installed in uniform or homogeneous soils. However, real-world scenarios may include isolated areas of extremely soft cohesive soils, leading to notable bulging at shallow and deep depths. It is crucial to consider this possibility as required. The suggested failure pattern for non-uniform soils according to (IS 15284 (Part 1) 2003) is depicted in Fig. 2.6.

In practical field applications, a granular pile is typically subjected to loading over a larger area than its own (Fig. 2.7). Consequently, it undergoes less bulging, resulting in enhanced ultimate load-bearing capacity and reduced settlement. This occurs because the load is shared by both the granular pile and the surrounding soil (IS: 15284 (Part 1) 2003).

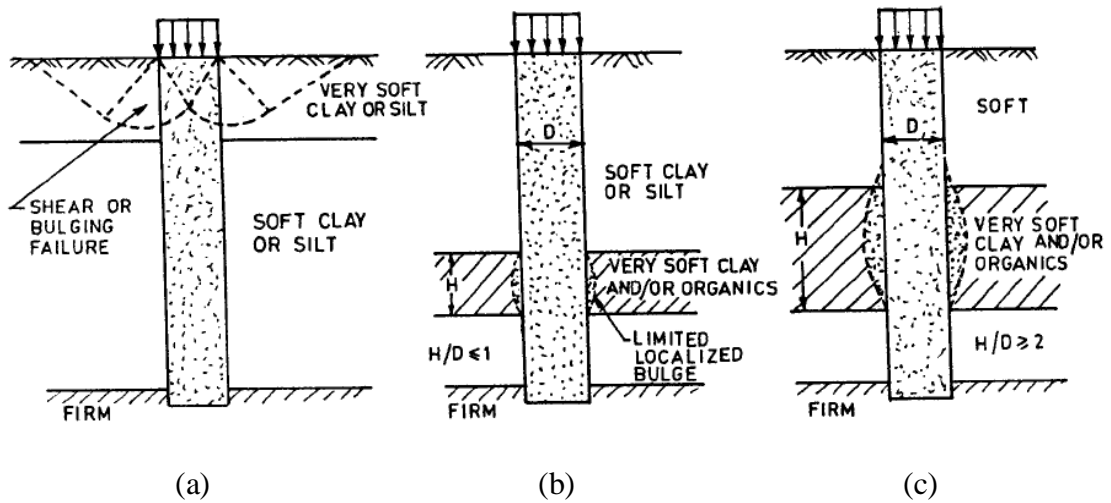


Fig. 2.6 Failure mechanisms of a single granular pile in a non-homogeneous soft layer according to (IS:15284 (Part 1) 2003), (a) Soft layer at surface- bulging or shear failure, (b) Thin very soft layer- contained local bulge, (c) Thick very soft layer-local bulging failure.

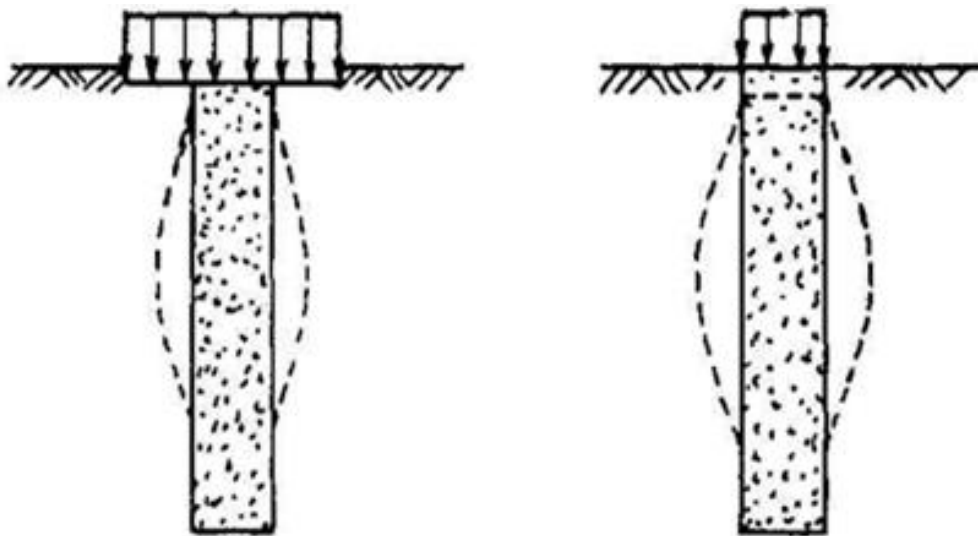


Fig. 2.7 Different types of static loadings applied to granular piles (IS: 15284 (Part 1) 2003).

2.2.4 Basic relationships

In practical foundation design, when any large infrastructure is supported by a larger number of granular piles, settlement and stability analyses often involve associating the tributary area of soil surrounding each pile with those depicted in Fig.

2.8(a). Depending on the spacing between the piles, the tributary area may vary. Although it typically forms a regular hexagon around the pile, it can be approximated as an equivalent circle of effective diameter (D_e) with the same total area. This resulting equivalent cylinder of material, with diameter D_e , enclosing the tributary soil and one granular pile, is termed the unit cell, as illustrated in Fig. 2.8(b). The granular pile is concentric to the exterior boundary of the unit cell. Boundary conditions associated with the unit cell are presented in Fig. 2.8(c).

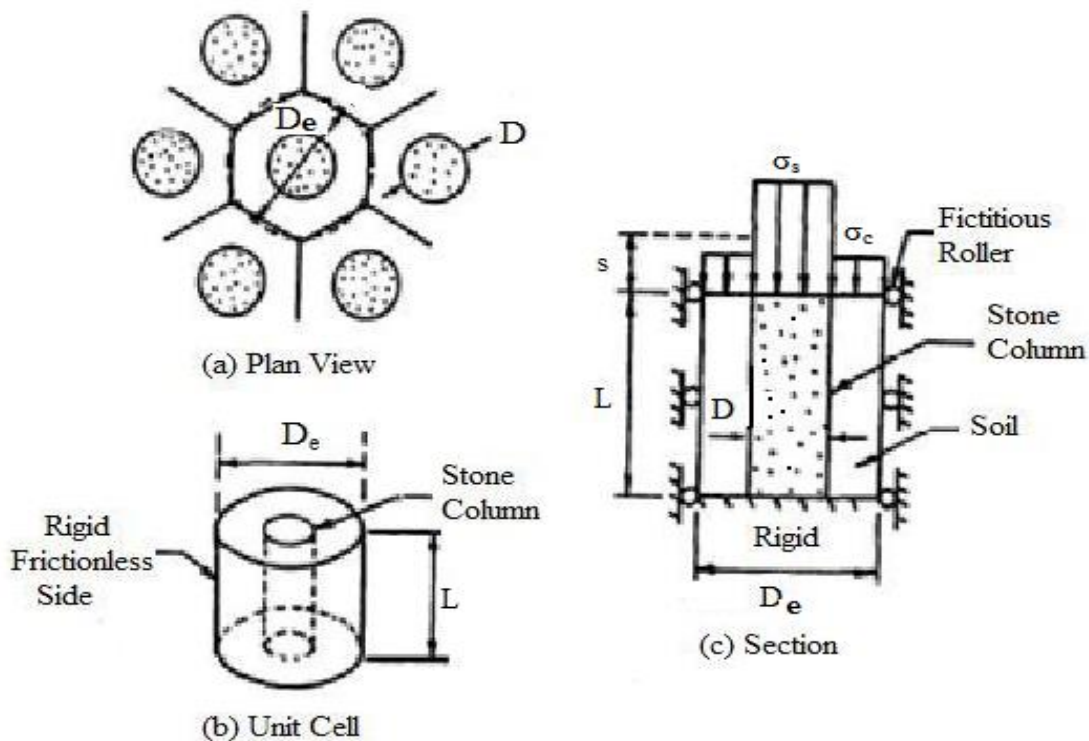


Fig. 2.8 Unit cell idealization (FHWA 1983).

Three types of granular pile arrangements, i.e., triangular, square, and hexagonal, are illustrated in Fig. 2.9. The triangular pattern offers the densest packing for the same granular pile spacing. The triangular pattern provides the densest packing for the same granular pile spacing. Some fundamental relationships, assuming the unit cell concept (FHWA 1983), are as follows:

(i) **Equivalent Diameter (D_e)**

For an equilateral triangular pattern of granular piles, the equivalent circle has an effective diameter D_e (Fig. 2.9) as given below:

$$D_e = 1.05s \quad (2.1)$$

For a square grid pattern,

$$D_e = 1.13s \quad (2.2)$$

For a hexagonal grid pattern,

$$D_e = 1.29s \quad (2.3)$$

where s is the spacing of granular piles

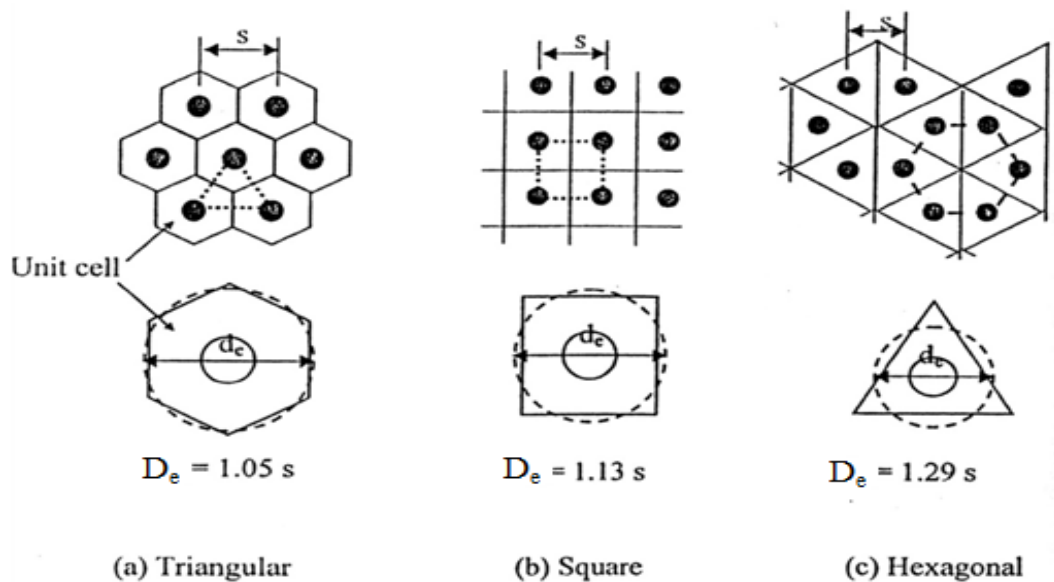


Fig. 2.9 Typical granular pile arrangements.

(ii) **Area replacement ratio (A_r)**

The volume of soil replaced by granular piles has an important effect on the performance of the improved ground. To quantify the amount of soil replacement, the area replacement ratio, A_r , is defined as the fraction of soil tributary to the granular pile replaced by the granular materials.

$$A_r = A_{GP}/A \quad (2.4)$$

where A_{GP} is the area of the granular pile after compaction, and A is the total area within the unit cell (Fig. 2.7a). Further, the ratio of the area of the soil remaining to the total area is then

$$\begin{aligned} a_c &= A_s/A \\ &= 1-A_r \end{aligned} \quad (2.5)$$

The area replacement ratio, A_r , can be expressed in terms of the diameter and spacing of the granular piles as follows:

$$A_r = C_1 \left(\frac{d}{s} \right)^2 \quad (2.6)$$

Where d is the diameter of the compacted granular pile, s is the center-to-center spacing of the granular piles, and C_1 is a constant dependent upon the pattern of granular piles used (for a square pattern, $C_1 = \pi/4$, and for an equilateral triangular pattern, $C_1 = \frac{\pi}{2\sqrt{3}}$).

For an equilateral triangular pattern of granular piles, the area replacement ratio is then

$$A_r = 0.907 \left(\frac{d}{s} \right)^2 \quad (2.7)$$

(iii) Stress Concentration

The distribution of vertical stress within a unit cell can be expressed by a stress concentration ratio n , defined as

$$n = \frac{\sigma_{GP}}{\sigma_{SB}} \quad (2.8)$$

where σ_{GP} is the stress in the granular pile, and σ_{SB} is the stress in the surrounding soft soil bed. The average stress σ , which must exist over the unit cell area at a given depth to satisfy the equilibrium of vertical forces within the unit cell for a given area replacement ratio, A_r , is as follows:

$$\sigma = \sigma_s A_r + \sigma_c (I - A_r) \quad (2.9)$$

where all the terms have been previously defined. Solving equations (2.8) and (2.9) for the stress in the clay and granular pile gives

$$\sigma_c = \frac{\sigma}{[1 + (n-1)A_r]} = \mu_c \sigma \quad (2.10)$$

and

$$\sigma_s = \frac{n\sigma}{[1 + (n-1)A_r]} = \mu_s \sigma \quad (2.11)$$

where μ_c and μ_s are the ratio of stresses in the soft soil bed and granular pile, respectively, to the average stress σ over the tributary area. For a given set of field conditions, the stress in the granular pile and surrounding soft soil bed can be readily determined using equations (2.10) and (2.11) if a reasonable value of the stress concentration factor is assumed based on previous measurements. The above two equations, which give the stress due to the applied loading in the granular pile and surrounding soil, are useful in settlement and stability analyses. Field measurements for granular piles have shown that the value of n generally lies in the range of 2 to 5 (Vautrain 1977; Goughnour and Bayuk 1979).

(iv) Settlement Reduction Ratio

Most approaches for estimating the composite ground's settlement assume unit cell idealization. The settlement reduction ratio is expressed as:

$$R = \frac{S_t}{S} \quad (2.12)$$

where S_t is the settlement of the composite ground, and S is the settlement of the unimproved ground or without granular pile.

2.3 Literature studies

2.3.1 Behavior of granular piles under static loading

This section provides a literature review on the performance of granular piles under static loading, both with and without geosynthetic encasements, focusing on aspects such as bearing capacity, bulging of granular piles, and load settlement of single and groups of granular piles. Given the study's focus on geosynthetic reinforced granular piles, only a concise literature review on unreinforced granular piles is included. A detailed literature review is presented in the following sections, which include experimental and numerical under single granular piles and granular pile groups.

2.3.1.1 Ultimate bearing capacity of unreinforced granular piles (q_{ult})

Several theories were derived to estimate the ultimate load-bearing capacity of a single granular pile surrounded by soft soil (Hughes and Withers 1974; Baumann and Bauer 1974; Wong 1975; Thornburn 1975; Balaam 1978; Aboshi et al. 1979; Goughnour and Bayuk 1979). However, most analyses have focused on single, end-bearing granular piles, with few researchers considering floating piles and groups of piles.

In many early analytical solutions, a triaxial state of stress is assumed in the granular pile, with both the pile and surrounding soil considered to be at failure (Hughes and Withers 1974; Wong 1975; Aboshi et al. 1979; Goughnour and Bayuk 1979). The lateral confining stress σ_3 , which supports the granular pile, is typically regarded as the ultimate passive resistance the surrounding soil mobilizes as the granular pile bulges outward against it. Since the granular pile is assumed to be in a state of failure, the ultimate vertical stress, σ_1 , can withstand is equal to the coefficient

of passive pressure of the granular pile, K_p , multiplied by the lateral confining stress, σ_3 . According to classical plasticity theory, this relationship can be expressed as:

$$\frac{\sigma_1}{\sigma_3} = \frac{1 + \sin \phi_s}{1 - \sin \phi_s} \quad (2.13)$$

where ϕ_s is the angle of internal friction of the granular pile and the stress ratio σ_1/σ_3 is the coefficient of passive earth pressure K_p for the granular pile.

(IS: 15284 (Part 1) 2003) introduced a method for calculating the ultimate bearing capacity based on the bulging of granular piles. According to this method, the limiting axial stress in the granular pile was thus determined as follows:

$$\sigma_v = \sigma_{rL} K_{p\ col} \quad (2.14)$$

where

$$\sigma_{rL} = \sigma_{ro} + 4c_u \quad (2.15)$$

$$\sigma_{ro} = K_o \sigma_{vo} \quad (2.16)$$

$$K_o = 1 - \sin \phi \quad (2.17)$$

$$\sigma_{vo} = \gamma 2D \quad (2.18)$$

$$K_{p\ col} = \tan^2 \left(45^\circ + \frac{\phi_c}{2} \right) \quad (2.19)$$

σ_v = Limiting axial stress in the granular pile when it approaches shear failure due to bulging,

σ_{rL} = Limiting radial stress,

c_u = Undisturbed undrained shear strength of soft soil bed surrounding the granular pile,

σ_{ro} = initial effective radial stress,

K_o = Average coefficient of lateral earth pressure,

ϕ = Effective angle of internal friction of soil,

σ_{vo} = Average initial effective vertical stress considering an average bulge
depth of two times the diameter of the granular pile,

γ = Effective unit weight of soil within the influence zone and

ϕ_c = The angle of internal friction of granular pile material.

According to other researchers, the limiting axial stress of the ordinary granular pile is presented below.

Mode of failure	Derived formula	Reference
Bulging	$q_{ult} = \left(\gamma_c z k_{pc} + 2C_o \sqrt{k_{pc}} \right) \frac{1 + \sin \phi_s}{1 - \sin \phi_s} \quad (2.20)$	Greenwood (1970)
	$q_{ult} = (cF'_c + qF'_q)(2.21) \quad \left(\frac{1 + \sin \phi_s}{1 - \sin \phi_s} \right)$	Vesic (1972)
	$q_{ult} = \left\{ \sigma_{ro} + c \left[1 + \log_e \frac{E}{2c(1+\nu)} \right] \right\} \left(\frac{1 + \sin \phi_s}{1 - \sin \phi_s} \right) \quad (2.22)$	Hughes and Withers (1974)
	$q_{ult} = \frac{1 + \sin \phi_s}{1 - \sin \phi_s} (4C_o + \sigma_{ro} + k_o q_s) \left(\frac{W}{B} \right)^2 + \left(1 - \left(\frac{W}{B} \right)^2 \right) q_s \quad (2.23)$	Madhav et al. (1979)
	$q_{ult} = k [0.5 \gamma_{sub} L_c + 5c_u] \quad (2.24)$	Ranjan and Rao (1987)
General shear	$q_{ult} = 2A_s \left(k_{pc} q_o + 2C_o \sqrt{k_{pc}} \right) + \left(\frac{1}{k_{as}} \right) (3d_s k_{ps} \gamma_c) \left(1 - \left(\frac{3d_s}{2L} \right) \right) \quad (2.25)$	Wong (1975)

	$q_{ult} = C_o N_c + \left(\frac{1}{2}\right) \gamma_c B N_\gamma + \gamma_c D_f N_q \quad (2.26)$	Madhav and Vitkar (1978)
	$q_{ult} = \left(\frac{1}{2}\right) \gamma_c B \tan^3 \psi + 2C_o \tan^2 \psi + 2(1-a_s) C_o \tan \psi \quad (2.27)$	Barksdale and Bachus (1983)
Punching	$\tau = (1-a_s) C_o + (\gamma_s z + \mu_s \sigma_z) a_s \tan \phi_s \cos^2 \theta \quad (2.28)$ $\mu_s = \frac{n}{1+(n-1)a_s} \quad (2.29)$	Aboshiet al. (1979)

Granular piles are frequently employed in groups to enhance foundation soils beneath structures like high-speed railway tracks, expressways, airport runways, hydraulic structures, ports, oil storage tanks, large-scale industrial facilities, etc. When granular piles are closely spaced, the bulging of one pile is counteracted by neighboring piles. This phenomenon, known as the "Group Effect," causes the load to be transmitted to greater depths in the group's center. Except for granular piles near the edge of the loaded area that are not uniformly contained, the group effect enhances the stiffness and strength of the piles as the load is applied. The applied load becomes a significant factor influencing the strength and stiffness of the piles.

Consequently, granular piles in large arrays under wide loaded areas such as embankments, stockpiles, or oil tanks exhibit superior performance compared to those under narrow strips and pad footings, where all piles are close to the edges of the footing. They are thus constrained only by unloaded ground (Greenwood 1970). (IS 15284 (part 1) 2003) proposed that the ultimate bearing capacity of granular pile groups (12 granular piles in a group) under axisymmetric condition, as shown in Fig. 2.10, where s = spacing between granular piles.

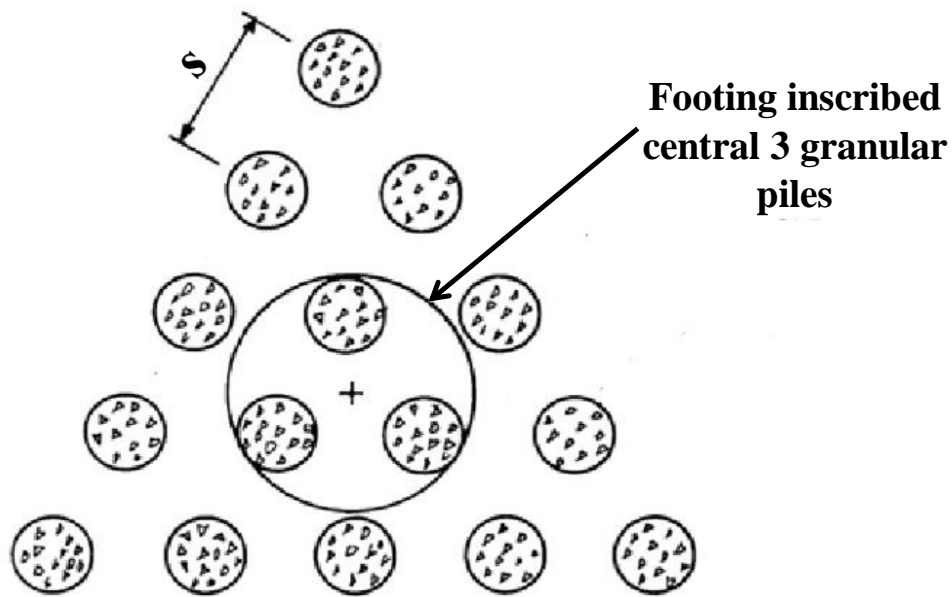


Fig. 2.10 Arrangement of a group of 12 granular piles under axi-symmetric condition (IS 15284 (part 1) 2003).

2.3.2 Granular piles subjected to static loading - Laboratory model studies

(Deb et al. 2010) developed a mechanical model to predict the behavior of geosynthetic-reinforced granular fill over soft soil with a group of granular piles under axisymmetric loading and assess geosynthetic reinforcement's effectiveness in reducing settlement and transferring stress. The effectiveness of geosynthetic reinforcement in reducing settlement and transferring stresses is influenced by granular pile stiffness and spacing, with a specific threshold ratio above 4 for the ratio between the spacing and diameter of granular piles.

(Gniel and Bouazza 2010) examined the behavior of geogrid granular piles in small-scale model tests and explained how geogrid encasement affects the influence of granular piles in soft soils. The methodology involved laboratory model testing on homogeneous clay beds, unit-cell idealization for testing group piles, and a two-stage

testing process, including consolidation and loading of clay-pile samples. The study's main findings include that encasing granular piles with geogrid resulted in a substantial decrease in vertical settlement, with an average settlement reduction of about 30% to 80%, depending on the degree of encasement. Group granular piles showed increased stiffness and reduced vertical settlements compared to isolated granular piles, indicating the importance of lateral confinement provided by the surrounding clay. Additionally, partial and full geogrid encasement of granular piles may offer innovative design solutions for various applications, such as controlling settlement in areas with compressible soil and reducing the number of granular piles needed while achieving the same reduction in vertical settlement.

(Murugesan and Rajagopal 2010) discussed the performance of single and grouped encased granular piles for enhancing soft soil ground. This study compares the performance of encased granular piles with ordinary granular piles and studies the use of geosynthetic encasement to enhance the behavior of granular piles in soft soils, emphasizing factors like encasement tensile strength and stiffness, granular pile diameter and highlighting the stiffer and stronger responses of encased granular piles compared to ordinary ones. They conducted an experimental study with model tests on granular piles to examine the impact of geosynthetic encasement on load-bearing capacity and developed design guidelines. The methodology involved wrapping granular piles with geosynthetic encasements, installing them by displacement method, and conducting static load tests in displacement control mode on ordinary and geosynthetic encased granular piles in a triangular pattern. The major findings include the load-bearing capacity and stiffness of granular piles, which can be increased by geosynthetic encasement, with encased granular piles showing stiffer and stronger responses. The benefit of encasement decreases with an increase in granular pile

diameter, favoring smaller-diameter granular piles for better performance. Furthermore, a design chart was developed to select geosynthetic encased granular piles and estimate the required geosynthetic tensile strength for maximum applied pressure.

(Najjar 2013) presented a state-of-the-art review of granular pile-reinforced soft soil systems under static loading, aiming to summarize and present the evolution of research on granular piles published after 2000. This study covers the laboratory testing, modeling, and analysis of soft soils reinforced with single granular pile and granular pile groups. This study also focuses on ordinary and geosynthetic encased granular piles encompassing design approaches, field/laboratory model tests, and numerical studies. The literature review section of this study delves into the design approaches and methodologies, summarizing key findings from prominent studies. It covers the studies related to estimating immediate and consolidation settlements of cohesive soil reinforced with granular piles and the development of quantitative methods for estimating settlement. Additionally, it explores empirical methods for computing the ultimate bearing capacity of single and group granular piles. This study provides detailed insights into the theoretical and empirical approaches, incorporating practical applications and considerations for various loading configurations on single and group granular piles.

(Ali et al. 2012) performed model tests on very soft soil bed improved with the single granular pile, including short, floating, and end bearing conditions with and without geosynthetic reinforcement. This study aimed to determine the relative improvement in the composite ground's failure stress due to different reinforcement types. Geotextile with a tensile modulus of 97.5 kN/m was employed as vertical reinforcement, and geogrid with an aperture size of 6 mm × 6 mm with tensile

modulus of 120 kN/m was used as the horizontal strip. The main findings include the similarity in failure stress between floating and end-bearing granular piles, the different failure modes between long and short piles, and the negligible impact of reinforcement on short floating piles. Also, a geogrid is the optimal encasement to employ as both horizontal and vertical encasement for end-bearing granular piles.

(Dash and Bora 2013) examine the impact of geosynthetic encasement on the behavior of floating granular piles in soft soil bed via laboratory model experiments, offering insights into the effect of geogrid encasement on the performance of granular piles in soft soil. The methodology involved the preparation of soil beds with uniform moisture content, forming granular piles using a replacement technique, recording load and displacement data of composite foundations using a computerized system, and presenting results in various forms. The major conclusion is that granular piles can enhance the behavior of soft soils, with partial encasement being more effective than full-length encasement. This study highlights the ideal length for floating granular piles to maximize performance improvement, approximately five times their diameter, while the optimum spacing is approximately 2.5 times the pile diameter.

(Yoo and Lee 2012) conducted full-scale field studies across two locations in Korea to investigate the behavior of geogrid-encased granular piles in soft soil beds using various measurement instruments. The main findings highlight the effectiveness of the geogrid-encased granular pile system in reducing lateral bulging, controlling bulging failure, and minimizing settlements compared to conventional granular piles and rammed aggregate piers. The geogrid encasement significantly improves the load-bearing capacity and reduces settlement in soft ground, highlighting the importance of proper encasement depth and geogrid stiffness for optimal reinforcement effects.

(Ali et al. 2014) performed laboratory model tests on single and groups of granular piles with and without geosynthetic encasement to assess the enhancement in the composite ground's failure stress attributed to various encasements. Their study focussed on 30 mm diameter granular piles, considering both end-bearing and floating cases under strain-controlled compressive loading. The testing involved configurations with both vertical encasement and horizontal discs. The significant findings include an improvement in the failure stress of composite ground, which is greater for end-bearing piles than floating piles for vertically encased and horizontal discs reinforced granular piles. Additionally, geogrid is the effective encasement for end-bearing granular piles, while geotextile and geogrid are equally effective for floating granular piles as horizontal circular discs and vertical encasement. Also, the full vertical encasement provides the most benefit in increasing the failure stress of the composite ground.

(Hong et al. 2016) performed an experimental study with similarity analysis to ensure comparable behavior between prototype-scale and model-scale geotextile-encased granular piles. The methodology involves conducting laboratory model tests on encased sand piles embedded in soft clay, using geotextiles of different stiffness and strengths, with similarity analysis to ensure comparable behavior between prototype-scale and model-scale piles. The study examines the influences of encasement mechanical properties on bearing capability and deformation behavior of granular pile improved ground.

(Gu et al. 2016) conducted laboratory model tests in a large-scale testing tank to investigate the effect of geogrid encasement on the ultimate bearing capacity, lateral bulging, and vertical deformations of granular piles in a soft clay bed. They studied the deformation patterns of encased granular piles and the reinforcement mechanisms

of geogrid encasement with varying encasement lengths. The major findings include the geogrid-encased granular piles, which significantly increased the ultimate load capacity of soft soil. The effective length of the encasement should be three to four times the diameter of the granular piles for optimal performance and economy.

(Miranda and Da Costa 2016) performed a laboratory based experimental study focused on triaxial compression tests on aggregate specimens in soft soil encased with geotextiles. This study mainly discusses geotextiles' impact on encapsulated granular piles' behavior in triaxial tests, highlighting improvements in strength and the influence on confining pressure and mobilized friction angle of the aggregates. The granular piles were built with two different densities of aggregates with and without geotextile encasements. The major findings include that encasing granular piles with geotextiles significantly improves their strength and performance. The deviator stress ratio demonstrates the reinforcing effect of geotextiles on aggregate samples. Also, the mobilized friction angle of the aggregates is lower in encased samples compared to non-encased ones.

(Fattah et al. 2016) conducted an experimental study to investigate the behavior of embankment models constructed on soft clay improved by ordinary granular piles (OGPs) and geogrid-encased granular piles (EGPs), highlighting the importance of factors such as spacing ratio, embankment height, and stress concentration ratio in the design and performance of stone-pile embankment systems. This study assesses the behavior in terms of the relationship between applied stress and settlement and understanding the impact of lateral bulging on the bearing capacity of the site. The main conclusions include the bearing improvement ratio increased with decreasing spacing of granular piles, highlighting a higher improvement in bearing capacity with

closer spacing. The bearing capacity of the site was influenced by the lateral bulging of the granular piles during loading.

(Fattah et al. 2016) were performed analytical studies on granular piles improved soft ground using the statistical analysis (SPSS program) to derive a general equation for estimating the bearing capacity of floating granular pile groups based on experimental work and previous studies. The study conducted experiments on different configurations of granular piles to address uncertainties in existing formulas. The study developed a general equation to estimate the bearing capacity of single and groups of granular piles, with the area replacement ratio (A_r) being the most influential parameter. The equation can be adopted to predict the bearing capacity of granular piles, considering factors like undrained shear strength, area replacement ratio, number of granular piles, and length-to-diameter ratio. The results suggest that the spacing between piles plays a significant role in determining the bearing capacity of granular piles.

$$q_u = 4c + 2A_r[c(K_p - 2) + c_s\sqrt{K_p}] \quad (2.35)$$

$$A_r = N_s\pi D^2/A_f \quad (2.36)$$

where,

c_s = The cohesion of granular pile material

N_s = Number of granular piles

D = Diameter of the granular pile

A_r = Area of the granular pile

A_f = Area of the footing

K_p = Passive earth pressure coefficient

(Bazzazian Bonab et al. 2020) conducted laboratory model tests on encased floating granular piles with specific diameters and lengths to study the influence of various positions of geotextile encasement, comparing vertical encasement, horizontal encasement, and combined vertical-horizontal encasement on the load-carrying capacity of the granular piles. The major findings include that ordinary granular piles fail to bulge due to a lack of lateral confinement, which can be addressed using encasement materials. Vertical-encased granular piles and horizontally encased granular piles both contribute to increasing the load-carrying capacity of the soil, with combined vertical-horizontal encased granular piles (VHEGPs) having the greatest increase in load-carrying capacity compared to VEGPs and HRGPs.

(Rathod et al. 2021) conducted extensive experimental tests to evaluate the effectiveness of using woven polypropylene material for encasing granular piles and comparing it with commercial woven geotextiles and non-woven geotextiles. The study also investigated the influence of vertical encapsulation on granular piles of different diameters. The key findings highlight the importance of the tensile strength of encasements in enhancing granular pile performance, the effectiveness of polypropylene textiles for encasement, the reduction in lateral displacement, and the increase in load-carrying capacity with different encapsulation conditions. The findings support using polypropylene textiles as a cost-effective alternative for encasing granular piles.

(Gu et al. 2022) examined the influence of geogrid encasement on the behavior of floating granular piles and provided insight into the load-displacement behavior, bulging deformation, load transfer mechanism, and radial stress of the geogrid encasement. The methodology involved plate loading tests on single granular piles with incremental vertical pressure application, measurement of hoop strains in the

geogrid encasement, and analysis of circumferential strains to understand the behavior of floating granular piles. The summary of this study emphasizes the positive impact of geogrid encasement on the behavior and performance of floating granular piles, supporting their effectiveness in enhancing bearing capacity and load transfer mechanisms in soft soil conditions.

(Ullah et al. 2022) performed an experimental study using small-scale physical models to investigate the bearing capacity performance of highway embankments supported on bottom ash piles reinforced with soft soil. The methodology involved conducting laboratory model tests with different area replacement ratios and granular pile length-to-diameter ratios, using pore pressure transducers and miniature pressure transducers to monitor excess-pore water pressure and vertical stresses. This study also determined the stress concentration ratio and developed a new equation for predicting the bearing capacity of the bottom ash piles supported embankments.

(Emam et al. 2022) investigate the behavior of encased granular piles using different types of aggregate materials to improve load capacity in soft soil. The methodology involved conducting laboratory model tests on very soft soil reinforced by encased granular piles using different materials, focusing on various variables such as granular pile type and material, type, and length of geosynthetic encasement. This study also emphasizes the benefits of using a sand pad, the superiority of geogrid over geotextile encasement, and the efficiency of partial encasement over total encasement. The main findings include that encased granular piles increase the ultimate load capacity of soft soil, partial encasement is more efficient than total encasement, and geogrid encasement improves soil performance by 18.1-26.6% compared to conventional piles, and geotextile encasement is more beneficial than geogrid for both total and partial encasement by 19.9-29.4% and 6.6-13.7%, respectively.

(Arulrajah et al. 2009) discusses the ground improvement techniques used in Malaysia's major high-speed railway project. This field study analyzes the various ground improvement methods employed to meet specific requirements, including maximum post-construction settlement, differential settlement, and degree of consolidation. The methodology involves installation, load testing, and field instrumentation for vibro replacement with granular piles for railway embankments. This study also provides detailed information on the treatment area ratio for granular piles, factors of safety for slope stability, and the time required for the degree of consolidation in sandy silts. The main findings include the successful use of granular piles to treat soils over a 14 km length of the railway line, with approximately 1,100,000 linear meters of granular piles installed to depths of 6-30 meters. The predicted total settlements were in the range of 0.3-0.5 meters, and safety factors for slope stability were greater than 1.5.

2.3.3 Granular piles subjected to static loading - Numerical studies

(Ambily and Gandhi 2007) investigating the performance of single granular piles and groups of seven granular piles under varying conditions, comparing experimental results with finite-element analyses, and developing design charts and procedures based on the findings. The methodology involved finite-element analyses using the PLAXIS 2D software package, experiments on a 100 mm diameter granular pile surrounded by soft clay, drained conditions for the clay, and Mohr-Coulomb's criterion for analyses. This study summarizes the key findings, including the failure mode of granular piles, the effect of spacing on axial capacity and settlement, the ratio of limiting axial stress to shear strength, the linear load-settlement behavior of the unit cell, the comparability of single and group pile test results, and the independence of stiffness improvement factors on the undrained shear strength of surrounding soil. The

major findings include that granular piles with spacing greater than three times the diameter do not significantly improve the ground.

(Khabbazian et al. 2010) investigate the influence of geosynthetic encasement on the behavior of granular piles in very soft soils, focusing on factors such as geosynthetic stiffness, granular pile material properties, dimensions, and in situ lateral earth pressure. The methodology involved three-dimensional finite element analyses using the ABAQUS program to study the behavior of granular piles with and without encasement in soft soil. Using geosynthetic encasement significantly improves the behavior of granular piles in very soft soils, increasing their strength and preventing lateral displacement. The stiffness of the encasement plays a major role in determining the granular piles' stress-settlement response and load-carrying capacity. The applied stress determines the optimal length of encasement for partially encased piles. However, this study is limited to numerical analyses and simulations without experimental validation, and the findings may not be directly generalizable to all real-world scenarios. Further research is recommended for validation through physical testing and exploration of behavior under different conditions.

(Ghazavi and Nazari Afshar 2013) conducted the laboratory model tests on granular piles with different diameters and lengths and numerical analysis using the finite element method (PLAXIS 2D) to study scale effects and reinforcement effectiveness. This study emphasizes the effectiveness of vertical reinforcing materials in increasing bearing capacity and stiffness, the importance of reinforcement length and strength, the superiority of VEGPs over OGPs, the variation of stress concentration ratio, and the impact of settlement and granular pile diameter on stress concentration ratio. The main findings include the increase in the bearing capacity of the granular pile with vertical reinforcing material compared to ordinary granular piles

and the positive correlation between the length and stiffness of encasement in VEGP and the granular pile bearing capacity.

(Mohanty and Samanta 2015) investigating the performance of granular piles in a two-layered soil system, examining the influence of top soft soil layer thickness and area replacement ratio on load-bearing capacity, and studying the soft soil layering effects on granular pile performance. The methodology involved laboratory tests on granular piles in two-layered soil systems, utilization of the unit cell concept, numerical analysis using PLAXIS-2D software, and modelling soft soil and granular piles with an elastic-perfectly plastic Mohr-Coulomb failure criterion under drained conditions. The major findings include that the thickness of the top soft and stiff clay layers influences the axial stress of the whole improved ground and granular pile. The stiffness improvement factor is maximized with the full depth of soft soil and remains constant for different depths of stiff clay. The vertical extent of bulging of the granular pile increases with the thickness of the top soft soil up to two times the diameter of the granular pile.

(Hasan and Samadhiya 2016) conducted experimental and numerical studies on floating single granular piles to investigate the performance of geosynthetic-encased granular piles in soft clays. The methodology involved adopting the unit cell concept, conducting experimental tests on different types of granular piles under various conditions, studying parameters like reinforcement and shear strength of clay, performing numerical analysis using PLAXIS 3D, and determining material parameters from laboratory tests. The granular pile is 75 mm in diameter and 375 mm in length, ensuring a floating condition. This study discusses using granular piles in soft clays to improve bearing capacity and reduce settlements, emphasizing the effectiveness of encasement on bearing pressure and the control of bulging in granular

piles. The ultimate bearing pressures were estimated using a double tangent method. Experimental results were compared with numerical analysis using PLAXIS 3D.

(Basack et al. 2016) developed an innovative finite-difference model employing modified Cam clay theory to examine the behavior of granular pile improved soft soil under static and cyclic loadings and to verify the results with existing laboratory and field test results. The analysis is based on assumptions about the deformations of the granular pile and soil, the direction of excess pore water flow, and the higher stiffness of granular piles compared to the surrounding soft soil. This study emphasizes the importance of considering the free-strain hypothesis, the limitations of the unit cell analogy, the faster dissipation of excess pore water pressure by granular piles, the behavior of granular pile-improved soft ground under cyclic loading, and the impact of granular pile stiffness on cyclic excess pore water pressure build-up.

(Castro 2017) analyzed the performance of groups of encased granular piles beneath a rigid footing, proposed a simplified approach based on the minor influence of granular pile arrangement, and evaluated settlement reduction and critical granular pile and encasement lengths. The methodology involves systematic 2D and 3D finite element analyses using PLAXIS software to study the performance of groups of encased granular piles. The major findings include the arrangement of encased granular piles, which has a minor influence on settlement reduction, with the area replacement ratio and encasement stiffness being critical factors. The specific pile arrangement only significantly affects the settlement reduction achieved with encased granular piles. Also, the critical length of encased granular piles for settlement reduction in a homogeneous soil layer is around 2-3.5 times the footing width.

(Hasan and Samadhiya 2017) conducted laboratory and numerical studies on end-bearing single granular piles to investigate the performance of geosynthetic-encased

granular piles in soft clays. The methodology involved laboratory model tests, numerical analyses, short-term-displacement control model tests, and comparison of results with FEM software, PLAXIS 3D. The granular pile is 75 mm in diameter and 525 mm in length, ensuring an end-bearing condition. Reinforced the granular piles with geosynthetics in the form of vertical encasement, horizontal strips, and combined vertical-horizontal encasement. This study concluded that there was a substantial enhancement in load-bearing capacity and stiffness by including geosynthetics in all three forms. The experimental results matched the PLAXIS 3D results well.

(Demir and Sarici 2017) performed experimental and numerical analysis on the behavior of granular piles with and without geogrid encasement in soft clay deposits and concluded that the granular pile method can improve soft ground and increase the bearing capacity, especially with geogrid encasement. This study covers various parameters such as the diameter of the granular pile, crushed stone's friction angle, geogrid rigidity, and encasement length. This study involved experimental tests using circular footings of different diameters, numerical analysis using the PLAXIS software validated by experimental tests, and parametric studies analyzing various parameters related to granular piles and geogrid encasement. The major findings include that using granular piles can increase the bearing capacity of clay deposits, with further improvement observed when the granular piles are encased with geogrid. The bearing capacity of granular piles and geogrid-encased granular piles increases with larger granular pile diameters and higher crushed stone friction angles.

(Debnath and Dey 2017) conducting laboratory model tests and numerical simulations using a finite element package ABAQUS to study the bearing capacity of geogrid-reinforced sand bed (GRSB) over encased granular piles in soft clay. The study includes preparing a test setup with specific dimensions, using steel pipes and

geotextiles for encasement, and varying parameters to analyze their impact on the system's performance. This study discusses using geogrid-reinforced sand beds over vertically encased granular piles to increase bearing capacity in soft clay, with significant improvements observed in bearing capacity, bulging reduction, stress concentration ratio, and determining optimal thickness and dimensions for the system. This study's major finding is determining the optimal thickness of USB and GRSB based on the maximum percentage improvement of load-carrying capacity. It is recommended that the thickness of the unreinforced sand bed (USB) be equal to 0.2 times the diameter of the footing and the thickness of the GRSB be equal to 0.15 times the diameter of the footing.

(Muzammil et al. 2018) discusses the behavior and optimization of geosynthetic encased granular piles (GEGPs) under oil storage tanks, emphasizing the impact of encasement stiffness and length on settlement and lateral deformation, and proposes optimal arrangements to balance performance and geosynthetic consumption. The methodology of this study involved initial studies in understanding load-carrying capacity, PLAXIS 3D modelling, geogrid elements for geosynthetic modelling, mesh refinement, and groundwater flow assumptions. The main findings include the geosynthetic encased granular piles (GEGPs) demonstrating reduced settlement and lateral deformation with increased stiffness. Also, an arrangement with inner granular piles fully encased and outer piles encased up to four times the granular pile diameter offers similar performance to fully encased granular piles with a 20% reduction in geosynthetic consumption.

(Hasan and Samadhiya 2018) performed laboratory model tests and numerical analyses on unreinforced and reinforced granular piles in soft clay based on the unit cell concept. This study mainly incorporates horizontal geogrid strips to reinforce

granular piles in soft clay. The laboratory model results were compared with FEM software, PLAXIS 3D. Incorporating geogrid strips led to a significant improvement in the ultimate load intensity and a reduction in the bulging of granular piles compared to ordinary ground.

(Ghazavi et al. 2018) investigate the effectiveness of horizontal reinforcement layers with various materials for granular piles with different diameters and extend the findings of tests to large real granular piles through numerical analyses. The methodology includes laboratory model tests on horizontally reinforced granular piles, numerical analyses using finite element analysis software (PLAXIS 2D), and various materials such as clay, crushed stone, geotextiles, and geogrid. The experimental setup involved a large steel tank with a displacement control system for applying vertical loads on the granular piles. This study also discusses the effectiveness of horizontally reinforcing granular piles, the benefits of using geogrid sheets over geotextile, the optimal vertical spacing between reinforcing sheets, and the comparison between horizontally reinforced and vertically encased granular piles. The findings suggest that horizontal reinforcement layers significantly increase the bearing capacity of granular piles, with geogrid sheets offering greater capacity and stiffness than geotextile. The optimal vertical spacing between reinforcing sheets is determined to be $0.25D$, and horizontally reinforced granular piles outperform vertically encased granular piles by up to 30%. This study also provides a comprehensive overview of the advantages and optimal parameters for horizontally reinforced granular piles compared to other methods, emphasizing the importance of proper reinforcement materials and spacing for maximizing bearing capacity.

(Jamkhaneh et al. 2020) performed numerical studies using ABAQUS finite element software for 3D modelling on the performance of geosynthetic-reinforced

granular piles in sandy soil, analyzing parameters like granular pile diameter, modulus of elasticity, geosynthetic type, and load ratio, with results including load intensity-settlement curves, lateral deformation, granular pile bulging, stress concentration, and load and stiffness ratios of the encasement. The study aims to understand the performance of reinforced granular piles with various geosynthetic materials over soft soil. The main findings of this study include the impact of encasement stiffness on load-bearing capacity, the effectiveness of encasing in smaller diameter piles, and the relationship between encasement presence and depth in terms of effectiveness.

(Jamkhaneh et al. 2020) conducted two-dimensional FEM analyses using PLAXIS 2D to examine the axial load intensity of uniform and non-uniform granular piles in soft soil by modelling them with different diameters and lengths. This study explores using non-uniform granular pile geometry to enhance bearing capacity and reduce construction material, demonstrating cost-effective solutions for ground improvement in soft soil. The main findings include non-uniform granular piles with a $d_2:d_1$ ratio of 1:5, which achieved the highest bearing capacity. The most economical design for granular piles was found at a $d_2:d_1$ ratio of 1:2 and a length ratio of $l_1:l_2 = 3:7$.

(Nav et al. 2020) investigated the mechanical performance of ordinary and reinforced granular piles using 3D finite element software ABAQUS assessed the impact of granular piles alone and in combination with geosynthetics on soft soil ground settlements. They also conducted parametric studies on pile grouping effects and studied the impact of granular piles' inter-pile spacing, length, and diameter on reducing settlements and bulging. The main findings included increased stiffness and bearing capacity with geosynthetic reinforcement, lower settlement and bulging in

reinforced granular piles compared to those without reinforcement, and maximum bulging at a depth of 3.5 m when varying the spacing between granular piles.

(Thakur et al. 2021) investigated the load settlement behavior and failure mechanisms of vertically and horizontally reinforced granular piles in the sand, comparing the effectiveness of different reinforcement methods and highlighting the importance of geotextile encasement for ground improvement. The methodology involved conducting tests on groups of 3 and 4 granular piles, comparing unreinforced and reinforced piles, and utilizing finite element modelling PLAXIS 2D to analyze the performance of granular piles, specifically considering soil properties and interface modelling for reinforced piles. This study concludes that horizontal reinforcement is more effective in enhancing load-bearing capacity and reducing lateral bulging than vertical encasement and suggests future research directions for combined vertical and horizontal reinforcement and detailed strain and earth pressure analysis. The findings are validated through finite element modelling and empirical relations, showing good agreement between experimental, numerical, and theoretical results.

(Miranda et al. 2021) performed the analysis of the critical length of encased granular piles, proposing general values for the critical pile length and highlighting the importance of considering plastic deformations in design. They conducted finite element analyses using PLAXIS codes, utilizing both 2D and 3D models, starting with a simple reference case, and performing parametric studies to analyze the influence of different parameters on the critical pile length. The major findings include that the critical pile length is influenced by factors such as area replacement ratio, soil strength, and soil stiffness. Also, the critical pile length is associated with the zone where plastic deformations occur.

(Kumar et al. 2023) discussed the geosynthetic-encased granular piles to improve load-carrying capacity and reduce settlement in soft soil, showing 15–25% improvements in load-carrying capacity for single piles in soft clay. It emphasizes the importance of geosynthetics in soil reinforcement and the benefits of encased granular piles over ordinary ones. Various factors, like spacing-to-diameter ratio and encasement conditions, are analyzed. They conducted FEM analysis using PLAXIS-3D, utilizing unit cell idealization for a single pile, validating material properties with a cylindrical mold, adjusting parameters to analyze soil settling behavior, and comparing single-layer-GEGP and double-layer-GEGP behaviors. The main findings include that the addition of a dual-layer geosynthetic encasement improves the vertical load-carrying capacity of the ground, enhances the axial load-carrying capacity of the granular pile, and provides insights into the influence of different pile parameters on load-carrying capacity.

2.3.4 Granular piles subjected to cyclic loading -Laboratory model studies

Granular piles are commonly employed to effectively support various types of foundations in diverse soil conditions, mainly in large infrastructure projects such as airports, railways, and road embankments, where dynamic loading is prevalent. Moreover, granular piles play a crucial role in mitigating liquefaction induced by earthquakes by increasing the density of the surrounding soil and facilitating drainage, thereby controlling the level of pore water pressure beneath the foundation. Additionally, granular piles enhance the total load-carrying capacity while reducing the stress level of the surrounding soil. Very few researchers have reported studies on granular pile composite soft soil foundations subjected to cyclic loading. The main literature studies on soft soil improved foundations subjected to cyclic loading are illustrated below.

(Jin Jian Jun 2008) performed shaking table tests on granular piles composite ground under cyclic loading, analysis of drainage effect, evaluation of rectangular and triangular reinforcement projects in preventing sand liquefaction, and observation of the acceleration of pore water pressure dissipation by granular piles. This study experimentally investigates the effectiveness of granular piles in preventing sand liquefaction and accelerating pore water pressure dissipation under cyclic loading. Also, this study explores different configurations of granular piles, examining the long-term effectiveness of granular piles in preventing liquefaction and comparing the efficiency of granular piles with other ground improvement techniques.

(Huang et al. 2016) determined the mechanisms of using granular piles to mitigate liquefiable ground. They conducted shaking table tests on saturated sand ground models with and without granular piles to study the mitigation mechanisms of liquefaction, focusing on comparing peak ground accelerations between reinforced and unreinforced ground. The model's granular piles had varying effects, including densification, drainage, and shear stress re-distribution. The excess pore water pressure, acceleration, and settlement results showed a notable enhancement in the liquefaction resistance of saturated sands during vibration in models with granular piles. The presence of granular piles slightly mitigated the build-up of EPWP, increased the overall stiffness of the ground, and notably reduced the settlement.

(Tang et al. 2015) discussed the effectiveness of liquefaction mitigation using the encased granular pile (EGP) technique for sand strata through FE simulations emphasizing the importance of GP diameter in reducing lateral deformation. The EGP approach effectively reduces lateral ground deformation by enhancing ground stiffening compared to the traditional GP method, with key parameters such as geosynthetic characteristics and GP diameter playing crucial roles in the remediation

efficacy. The major findings include that GP and EGP remediation methods effectively reduced lateral deformation in sand strata. Using a geosynthetic with larger tensile stiffness (J) and thickness (t) values significantly decreased lateral ground deformation in the sand stratum.

(Cengiz and Güler 2018) performed laboratory and field experiments, finite elements methods, and analytical models to evaluate and compare the behavior of geosynthetic encased piles (GEGPs) and ordinary piles (OGPs) during and after seismic excitations using 1-g model tests. The major findings include reduced settlements in unit cells with end-bearing granular piles compared to floating OGPs during earthquake loading. Different strain distribution patterns in granular piles reinforced with different geotextiles were reported under seismic impact.

(Yoo and Abbas 2019) performed laboratory model tests on a reduced-scale model to analyze the behavior of geosynthetic encased granular pile (GEGP) improved soft soil bed under axial cyclic loading. This study considered major parameters such as loading frequency, amplitude, and encasement length. The major findings were that GEGPs in soft soil beds provide more benefits under cyclic loading than static loading. The effectiveness of encasement is enhanced with lower loading frequency and/or lower cyclic loading amplitude under cyclic loading. Also, the full encasement is crucial for maximizing the performance of granular piles under cyclic loading.

(Yoo and Abbas 2020) conducted laboratory model tests on isolated geosynthetic encased granular piles of GEGPs at two different sites in Korea using specific crushed stones and various measurement instruments. The objective of this study includes investigating the improvement in load-carrying capacity and settlement reduction of a GEGP, exploring the effect of geogrid encasement length, and comparing settlement response and bulging of different types of granular piles. This study highlights the

effectiveness of the geogrid-encased granular pile system in reducing lateral bulging, controlling bulging failure, minimizing deflection, and improving load-carrying capacity, emphasizing the importance of optimal encasement length and geogrid stiffness based on ground conditions.

(Cai et al. 2020) conducted cyclic vibration tests on the subgrade, simulating dynamic loads generated by a train under different conditions and analyzing dynamic parameters at various subgrade positions. Field tests were conducted under natural and immersion conditions to study the dynamic response of the subgrade. The major findings include the dynamic response of the subgrade weakens as the distance from the vibration source increases. Also, the dynamic parameters of the subgrade increase linearly with higher train speed and axle load, with larger increments closer to the vibration source.

(Zhang et al. 2020) performed laboratory model tests to investigate the responses of geosynthetic-encased granular piles (GEGPs) under vertical cyclic loading in soft clay bed and examining factors influencing stress distribution, settlement, excess pore water pressure, and lateral bulging, with a focus on how different parameters affect these responses. The experimental results assessed the effects of different parameters on the vertical stress of the granular pile, settlement of the loading plate, lateral bulging, and the effective dissipation of excess pore water pressure through drainage channels. The geosynthetic encasement is crucial in preventing clay obstruction of drainage channels and ensuring effective drainage. Future research could focus on optimizing parameters such as encasement length, pile diameter, loading amplitude, and loading frequency to enhance the behavior of GEGP systems in soft soil conditions. Further studies could explore the mechanisms behind stress distribution,

settlement behavior, and pore water pressure dissipation to improve the efficiency and effectiveness of these systems.

(Karkush and Jabbar 2022) conducted experimental studies to investigate the effects of different patterns of floating granular piles and the development of excess pore water pressure on soft clay under cyclic loading through physical model tests to assess soil-bearing capacity, excess pore water pressure, and settlement. This study analyzed the improvement in geotechnical properties based on the area replacement ratio of granular piles and observed different patterns of pore water pressure behavior with varying numbers of loading cycles. The main findings include an increase in soil-bearing capacity, reduced excess pore water pressure and settlement, and improved geotechnical properties with a higher area replacement ratio of granular piles in enhancing geotechnical properties under cyclic loading.

(Gao et al. 2021) investigated the bearing characteristics of geosynthetic encased granular piles (GEGPs) under static and cyclic loading. Also, this study examines the effectiveness of GEGPs in reducing settlement and soil stress in composite foundations under cyclic loading, emphasizing the importance of parameters like the ratio of length to diameter and the strength of wrapping material. The methodology involved a combination of laboratory experiments, numerical simulations, monitoring of displacement of soil particles, and particle flow microscopic numerical simulation to investigate the performance of GEGPs under cyclic loading. The major findings include GEGPs effectively reduce settlement and soil stress, with performance influenced by L/D ratio and wrapping material strength.

(Cui et al. 2023) conducted cyclic triaxial tests on coarse-grained soil reinforced with geogrids using a triaxial apparatus, considering cyclic stress amplitude, confining pressure, and a number of geogrid layers. This study presents findings from cyclic

triaxial tests highlighting the effectiveness of geogrids in reducing accumulated deformation under high-cycle traffic loading, with potential implications for subgrade design and stability assessment.

(Banerjee et al. 2023) explored the feasibility of recycling overburden (OB) as an alternate track sub-ballast material in railways and filling the research gap by investigating the behavior of OB under cyclic loading and providing detailed laboratory investigations on its reuse as sub-ballast material. The methodology involved experimental investigations, twelve cyclic model tests, geocell reinforcement, developing a three-dimensional numerical model, determining stiffness parameters, applying sinusoidal cyclic loading, and using artificial neural networks for prediction. The major findings include that geocell reinforcement combined with coal mine OB as sub-ballast can effectively reduce track deformations and stabilize the track under cyclic loading. A shallow OB-sub-ballast thickness with geocell reinforcement can prolong track maintenance cycles and reduce maintenance costs. This study provides a sustainable solution for utilizing coal mine OB waste in railway construction, contributing to environmental sustainability.

(Shahu et al. 2023) conducted laboratory model and FEM studies on groups of granular piles under static and cyclic loading conditions similar to transportation routes. They performed 1-g reduced lab experiments to study the bearing and settlement performance of floating and end-bearing granular piles in very soft clay beds with varying undrained shear strengths. The methodology of this study includes preparing the soft clay beds, constructing the granular piles, applying cyclic loading, and conducting finite-element analyses to validate the experimental results. The major findings include cyclic loading induces settlements 4-11 times greater than monotonic loading under the same stress levels. Also, the end-bearing granular piles

are more effective than floating piles in improving bearing capacity and reducing settlements.

2.3.5 Literature review on recycled tire materials

The recycled tire materials from scrap tires mixed with traditional construction materials had limited applications in past studies. Few studies have reported characterizing the sand-rubber tire shred mixtures, but very few studies on aggregates-tire chips mixture. This section provides a comprehensive literature review of the response of recycled tire mixtures with traditional construction materials under static and dynamic loads.

(Edil and Bosscher 1994) evaluated the engineering properties of shredded scrap tires for construction applications, provided recommendations for testing and specifying tire chips, and highlighted the benefits of using scrap tires in construction projects. The methodology involved investigating the engineering properties of shredded scrap tires for reuse in construction, focusing on characteristics like compaction, compressibility, strength, and hydraulic conductivity by developing new test methods or modifying existing methods. The main findings of this study included assessing the engineering properties of shredded scrap tires for construction applications, highlighting the flexibility and compressibility of tire chips compared to soil particles, and recommending the mixing of sand to reduce hydraulic conductivity and compressibility.

(Kaneko et al. 2013) analyzed the seismic response characteristics of tire chips and tire chip-sand mixtures in terms of damping ratio, as well as determined the effectiveness of tire chips in preventing soil liquefaction and their seismic isolation effects on saturated sand deposits during earthquakes. The methodology involved pseudo-dynamic response tests on model grounds with tire chip-mixed sand or

alternating sand and tire chip layers, using simple shear tests under undrained conditions. Tire chips demonstrated significant damping and seismic isolation effects, reducing excess pore-water pressure and preventing liquefaction. The effectiveness of tire chips increased with higher mix ratios and when placed at deeper locations or in thicker layers. Pure tire chip layers at the bottom of sand layers were more effective in preventing liquefaction than mixing tire chips with sand.

(Ahn and Cheng 2014) examined the dynamic behavior of Tire Derived Aggregate (TDA) backfill under simulated earthquakes using a full-scale shake table test. This study discussed the main test results, such as accelerations, wall displacements, and dynamic pressures. The major findings included evaluating TDA backfill performance under simulated earthquakes and comparing it with conventional soil backfill, showing increased wall sliding but decreased cyclic stress on the wall.

(Marto et al. 2013) performed direct shear tests on mixtures of sand and tire chips with different weight percentages under three normal stresses. This research reported that adding tire chips can improve soil shear characteristics. The shear parameters, including the angle of internal friction and cohesion, and the effects of different parameters in the experiments were analyzed, and adding tire chips can improve the shear characteristics of the soil.

(Ahn et al. 2015) recycled the end-of-life tires (ELTs) into a tire-derived aggregate (TDA) by shredding waste into different sizes ranging from 12 to 305 mm. This study presents the material properties of large-size TDA used in civil engineering applications, including unit weight, shear strength, compressibility, and lateral earth pressure coefficient. Large-size TDA is typically used as lightweight fill material for embankments, dams, foundations, and retaining walls.

(Mittal and Gill 2018) conducted experimental studies on Tire chip Reinforced Sand (TRS) and Geogrid Reinforced Sand (GRS), varying parameters, compared the results of TRS and GRS, and examined their combined behavior. The major finding is that adding tire chips significantly increased bearing capacity at low and high strains. Also, tire chip-reinforced sand (TRS) performed better than geogrid-reinforced sand (GRS) at all strain levels. The bearing capacity ratio (BCR) can be further increased to 11 by combining TRS with GRS.

(Shariatmadari et al. 2018) investigated the utilization of tire shreds and tire crumbs from scrap tires as alternative materials for granular pile construction, evaluated the effects of adding tire shreds on the mechanical properties and deformation of granular piles, and found new applications for waste tire materials in geotechnical engineering. The methodology involved conducting large-scale direct shear box tests and oedometer tests to evaluate the effects of adding tire shreds on the mechanical properties and deformation of granular piles, determining specific gravity using ASTM standards, and installing granular piles in soft soil for testing. They considered three sizes of tire shreds, namely coarse, medium, and small. The major findings include reusing tire waste in granular piles, which improves performance and reduces construction costs. The shape and percentage of tire content influence the shear strength and axial bearing capacity of granular piles. The highest friction angle is achieved with 20% planar-shaped medium tire content.

(Mistry 2021) presented the critical review on the reuse of waste tire products as a soil reinforcing material to explore the potential of waste tire products in enhancing the mechanical properties of clayey soil. The objective is to review the existing literature on the use of waste tire products for ground improvement and to identify the effects of different waste tires on consistency limits, compaction characteristics,

strength characteristics, compressibility characteristics, permeability, and California-bearing ratio of cohesive soils. The review includes studies on the effects of waste tire products on soil reinforcement, including using different waste tires such as rubber chips, crumb rubber, and tire fibers. The review's main findings indicate that using waste tire products in ground improvement can be economical for the construction industry. The inclusion of waste tire products has been shown to reduce shrinkage, improve unconfined compressive strength, and enhance the mechanical properties of clayey soil. However, the review also highlights the need for further investigations and research studies to consolidate the findings and explore the potential utilization of waste tire products in constructing highway/railway embankments and other field applications.

(Das and Bhowmik 2020) evaluated the cyclic performance of sand mixed with crumb rubber. They performed torsional resonant pile tests to examine the cyclic performance of sand mixed with crumb rubber at low-strain conditions. This study mainly focused on determining the shear modulus and damping ratio concerning various influencing parameters such as strain level, confining pressure, and relative density for both pure sand and sand-crumb rubber mixtures. Also, this study compared the effect of different sizes of crumb rubber particles on the cyclic performance of sand-crumb rubber mixtures. The major findings include the shear modulus is directly proportional to relative density and confining pressure, with higher values observed for larger-sized crumb rubber particles. Also, the damping ratio is inversely proportional to the confining pressure and decreases with increased rubber content for mixtures with different sizes of crumb rubber particles.

(Mittal and Gill 2020) provided sustainable solutions for the disposal of waste tires by conducting experimental studies on strip footing resting on Tire-chip Reinforced

Sand (TRS). They conducted laboratory model footing tests on sand reinforced with waste tire chips using locally available sandy soil and compared the results with geogrid reinforcement. The parameters studied included tire-chip content, TRS zone depth, and TRS's relative density. The major findings included the TRS exhibited superior pressure settlement behavior compared to geogrid-reinforced sand up to a 10% settlement ratio. The optimum tire-chip content for the highest improvement in bearing capacity ratio was 20% by weight at low strains and 40% by weight at high strains. The TRS significantly improved pressure settlement behavior at both low and high strains. This study mainly discusses the benefits of using waste tires in enhancing soil properties, improving bearing capacity, and reducing settlements, highlighting the superiority of Tire-chip Reinforced Sand (TRS) over geogrid reinforcement in terms of performance and cost-effectiveness while also addressing the environmental concerns associated with waste tire disposal.

(Soltani et al. 2020) investigated the effects of TDA content and gradation on soil properties through ten mix designs, including standard proctor compaction, oedometer, swelling, and unconfined compression tests. Soil and TDA were blended in dry form, water was added to achieve optimum water content, and samples were prepared for testing. The mixing of the soil with tire-derived aggregates (TDA) at different contents (5%, 10%, and 20% by dry mass) using three different TDA sizes (TDA-F, TDA-M, and TDA-C) to improve geotechnical properties. This study emphasizes the effectiveness of TDA materials in reducing swelling potential and improving strength-related features of clay soil, with TDA contents up to 10% being optimal mix design choices, especially with TDA-M size variants. This study highlights the significance of TDA gradation and size in influencing geotechnical

properties and suggests TDA as a sustainable alternative to traditional stabilization methods.

(Moussa et al. 2021) emphasizes the importance of examining the cyclic properties of larger tire-derived aggregates (TDA) to understand their behavior under cyclic loads, mainly focusing on Type A TDA with a maximum aggregate size of 25.4 mm. The methodology involved conducting large-scale undrained cyclic triaxial tests on Type A TDA, preparing specimens with specific dimensions, removing protruding steel, and calculating damping ratios based on the area of hysteretic curves. The major findings included that the shear modulus of Type A TDA ranges from 244 to 2,901 kPa. Damping ratios of TDA were calculated and found to be significant, indicating the material's potential for vibration-dampening applications. This study mainly emphasizes the need for more experimental data on larger aggregate sizes of TDA, presents the range of shear modulus values for Type A TDA, and describes the method for calculating damping ratios.

(Zhang et al. 2022) investigated the effect of TDA on the static and dynamic behavior of TDA-sub ballast mixtures, evaluating the mechanical properties through large-scale tests, determining the optimal tire content, and promoting the application of TDA in railway engineering. The major findings included the addition of TDA to sub-ballast mixtures, which decreases stiffness, shear dilatancy, and modulus of resilience while increasing energy dissipation capacity. Also, this study introduces the concept of the equivalent inter granular void ratio and proposes empirical formulas to evaluate the mechanical indexes of the mixtures. The evaluation criteria suggest that TDA chips enhance the properties of the mixtures, with an optimal tire content of around 20%.

(Kumar et al. 2020) conducted laboratory tests on untreated and treated swelling clay specimens, mixing different amounts of granulated scrap tires with treated soil samples, investigating the effects of different percentages of cement or lime on the soil-tire mixture, and performing various tests, including index properties, density, California Bearing Ratio, swelling potential and compressive strength tests. The shredded scrap tires were mixed with swelling clay at different percentages (5%, 10%, and 15% by weight of soil) and mixing different percentages of either cement or lime (0% to 6% by soil weight) to the soil-granulated scrap tire mixture. Mixing scrap tires with swelling clay decreases swelling potential and improves strength, offering an environment.

(Ding et al. 2021) conducted consolidated undrained monotonic and cyclic triaxial testing to determine the liquefaction potential and dynamic parameter characteristics of granulated rubber-sand mixtures, following ASTM standards. The study also investigated shear strength, liquefaction characteristics, and dynamic parameters at medium shear strain levels. The major findings included that the shear strength of the mixture increases with increasing granulated rubber content up to 10% and then decreases. The dynamic pore water pressure decreases with increasing granulated rubber content and confining pressure and increases with increasing cyclic stress ratio and frequency. The change in shear modulus is inversely proportional to the change in granulated rubber content and frequency and is directly proportional to the change in confining pressure. This study highlights the optimum granulated rubber content, which was determined to be around 10%, and the addition of granulated rubber was found to improve liquefaction resistance and damping ratio, making it a potential material for seismic mitigation and energy dissipation.

(Amanta and Dasaka 2022) investigated the cyclic properties and liquefaction performance of tire chips and sand-tire chip mixes, determined the liquefaction potential and cyclic properties of sand-tire chip mixes with varied proportions, and suggested an optimum mixture based on the performance of the mixes with different tire chip contents. The methodology involved conducting strain-controlled cyclic triaxial tests on sand-tire chip mixes with varying proportions of sand and tire chips, considering confining pressure, strain amplitude, and tire chip content as variables. This study aimed to investigate the mixes' dynamic properties and liquefaction behavior, proposing a predictive relation for shear modulus based on shear strain and confining pressure. The results obtained can aid in evaluating the materials' response in civil engineering applications, particularly in earthquake-prone areas. The main findings include the high resistance of pure tire chips to liquefaction, increased liquefaction resistance and threshold shear strain by adding tire chips to sand, and decreased shear modulus and increased damping ratio in the mixtures.

(Moussa and El Naggar 2023) investigated the dynamic properties of tire-derived aggregates (TDA) in various civil engineering applications, focusing on the effect of TDA type A particle size on the dynamic response, highlighting the advantages of using TDA, and proposing a model to estimate shear modulus at small strains. The methodology involved conducting undrained strain-controlled cyclic triaxial tests on TDA specimens with different maximum particle sizes, comparing them to granulated rubber specimens. The tests were conducted with consolidation stresses ranging from 25 to 200 kPa and shear strains ranging from 0.1 to 10%. The setup included advanced pressure volume controllers, a back-pressure transducer, a digital data recorder, and a PC system for data processing. Samples were compacted with an energy corresponding to 60% of the standard Proctor energy, and consolidation was

achieved by gradually increasing chamber pressure while maintaining a constant back pressure. The main findings included the comparison of stiffness between TDA specimens of different particle sizes, the significant difference in damping capacity between TDA and granulated rubber, and the importance of considering particle size in the dynamic responses of TDA.

2.4 Summary

The major problems associated with soft soil beds are low bearing capacity, high compressibility, excessive settlements, low permeability, and high liquefaction potential. Hence, it is imperative that these soft soils must undergo adequate ground improvement before construction activities commence. Although several ground improvement techniques are available, utilizing granular piles is still considered a highly regarded and effective method. Granular piles offer sufficient improvement to soft soils by enhancing their shear strength, reducing excessive and differential settlement, and accelerating consolidation by shortening horizontal drainage paths. Consequently, they have been widely adopted for various projects, including highway embankments, industrial facilities, and residential structures.

This chapter reviewed various studies on granular piles subjected to static loading (both experimental and numerical studies) and cyclic loading. Furthermore, this chapter also discussed commonly adopted design approaches and construction methods. Over the past three decades, extensive research has been conducted to examine the behavior of granular piles in soft soils subjected to static loading. However, in numerous engineering projects such as oil storage tanks filling and discharging, embankments for roads, railways, airports, and ocean banks, the surcharge loading does not occur instantaneously but changes gradually over time. Especially, the high demand for high-speed railway upgrades has become a topic of

discussion in rapidly developing countries like India. Furthermore, it has to be addressed that the exact behavior of foundation on unimproved soft soil and on granular pile improved soft soil composite is not fully understood.

So, the behavior of granular piles under different loading sequences, such as static and cyclic loading, is an important consideration for understanding the general behavior of granular pile foundations. While some researchers have studied this topic under static loading, the question is whether a granular pile would behave similarly (interms of settlement and bulging) under cyclic loading? Additionally, what are the consequences of enhanced soils' threshold stress relative to static stress failure? And how does the cyclic loading frequency and amplitude influence the overall behavior of improved soils?

Furthermore, this chapter includes past studies regarding the application or utilization of various types of recycled tire materials from scrap tires in various civil engineering applications. The present study aimed to address the aforementioned questions and to provide a better understanding of the behavior of granular piles composed of tire chips - aggregates mixture under static and cyclic loading applications.

2.5 Research gap

- Despite the favorable engineering properties of recycled scrap tire derivatives, their application in civil engineering remains limited. This study is primarily motivated by the need to enhance the confidence of the engineering community in utilizing ELTs in civil engineering projects, particularly geotechnical applications. To achieve this, the research aims to offer a simple methodology for selecting the optimum mix proportions of tire chips-

aggregate mixtures and determining the engineering design parameters of these mixtures.

- ❑ No literature could be found on the behavior of granular piles composed of tire chips - aggregates under static and cyclic loading.
- ❑ Researchers have employed either geotextile or geogrid as encasement materials in granular pile applications. Still, no research has been carried out using combi-grid (a combination of geotextile and geogrid) as an encasement material.
- ❑ Very limited research has been conducted on the behavior of granular piles subjected to cyclic loading. Therefore, aspects such as cyclic loading amplitude and frequency and quantifying the amount of cyclic-induced settlement associated with these factors require further investigation.