CHAPTER 2

LITERATURE REVIEW

2.1 General

Granular columns, also referred to as stone columns, have been extensively used for ground improvement to support structural foundations (Bouassida et al. 1995). Various literatures published in the past have established the effectiveness of granular column foundations in soft soils. An overview of soft soil improvement techniques using granular columns has been provided in this chapter. The sub-sections further cover basic information regarding the working of granular columns, construction methods, and failure mechanisms.

Granular columns are used to provide sustainable and economic solutions in ground improvement for the development of transportation infrastructure like railway and highway embankments and large-scale industrial and storage facilities (Fig. 2.1). The literature associated with the application of granular columns has been included under subsections namely, behavior of granular columns under static loading, behavior of granular columns under cyclic loading, numerical studies on the behavior of granular columns and studies on the use of plastic waste and recycled materials in granular columns. The gap in the research area identified through the literature survey has been included at the end of the chapter.

A basic overview of granular columns covering the working principle and construction methods is discussed in section 2.2. Section 2.3 discusses geosynthetics and their functions. A detailed discussion of the literature on past studies is covered in section 2.4. Section 2.5 elaborates on the research gaps identified from the literature survey conducted as a part of this study

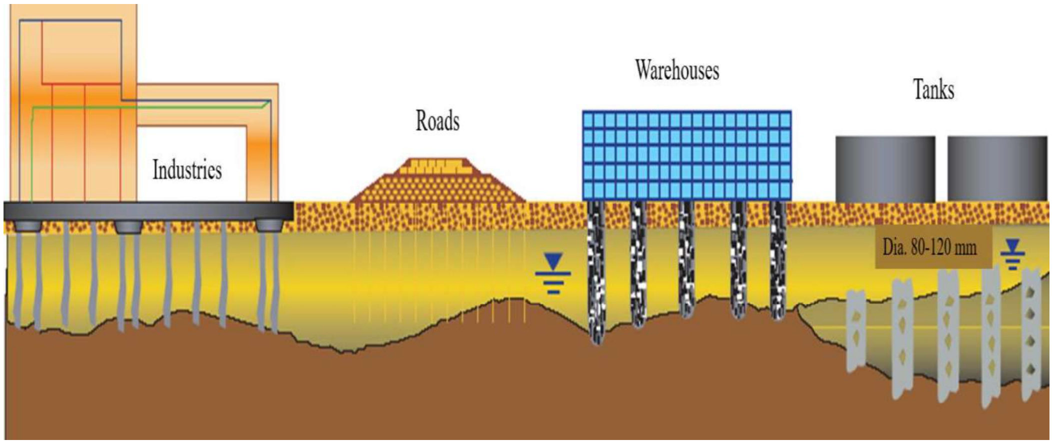


Fig. 2.1 Some applications of granular columns supported soil foundations (Reddy 2009).

2.2 Background

2.2.1 Working principle of granular column

The improvement of soft soil foundations through the installation of granular columns is driven by three primary mechanisms:

- **Reinforcement:** The inclusion of stiffer materials, such as crushed stone or gravel, within the soft soil increases the overall strength and stiffness of the ground.
- **Densification:** The installation process compacts the surrounding soil, enhancing its density and shear strength.
- **Drainage:** Granular columns act as vertical drains, accelerating the consolidation of the subsoil by allowing quicker dissipation of excess pore water pressure under loading.

The axial load-bearing capacity of granular columns largely depends on the passive earth pressure mobilized due to the bulging of the columns. This bulging resistance is influenced by the frictional properties of the surrounding soil. In extremely soft soils, the lateral confinement is minimal, resulting in lower load-bearing capacity and excessive deformation due to unrestrained bulging.

Additionally, the soft soil may intrude into the voids of the granular material, which reduces the column's strength by lowering inter-particle friction. This intrusion also decreases the column's permeability, slowing down the drainage process and hindering the dissipation of pore water pressure.

2.2.2 Construction methods of granular column

The successful improvement of soft and very soft soils using granular columns depends heavily on selecting an appropriate construction technique and ensuring accurate on-site implementation. The general process involves creating a borehole, filling it with selected granular material, and compacting the material to meet the required strength criteria. The choice of granular material and installation method varies based on site-specific conditions and engineering demands. Globally, several methods have been developed and employed depending on equipment availability and proven effectiveness. The primary construction methods are categorized as follows:

2.2.2.1 Non-displacement method

In the non-displacement technique, soil is removed through boring before the installation of the granular column. The excavated hole is then backfilled with granular material, which is compacted in layers. Since the installation does not displace the surrounding soil, no densification of the adjacent soil mass occurs. This method is particularly suitable for use in sensitive soils where displacement may cause instability or loss of strength.

Rammed Granular Column System:

One widely used non-displacement technique is the rammed granular column method, also referred to as the cased borehole method. Originally proposed by (Datye and Nagaraju 1975), this method is commonly applied in cohesive soils.

- A piling rig equipped with a casing pipe bores into the ground.
- The casing pipe stabilizes the borehole walls and minimizes disturbance to the surrounding soil.
- Excavated soil is removed using a bailer.
- Granular material is then introduced in stages into the borehole and compacted by ramming with a heavy falling weight (typically 15–20 kN dropped from a height of 1.0–1.5 m).
- As the material is compacted, the casing pipe is gradually withdrawn.

The strength of the column is achieved through lateral confinement provided by the adjacent soil. Therefore, it is essential to preserve the shear strength of the surrounding ground during construction. This method is particularly effective in clays with low sensitivity. Fig. 2.2 illustrates the installation of a granular column using the rammed method (Datye and Nagaraju, 1975).

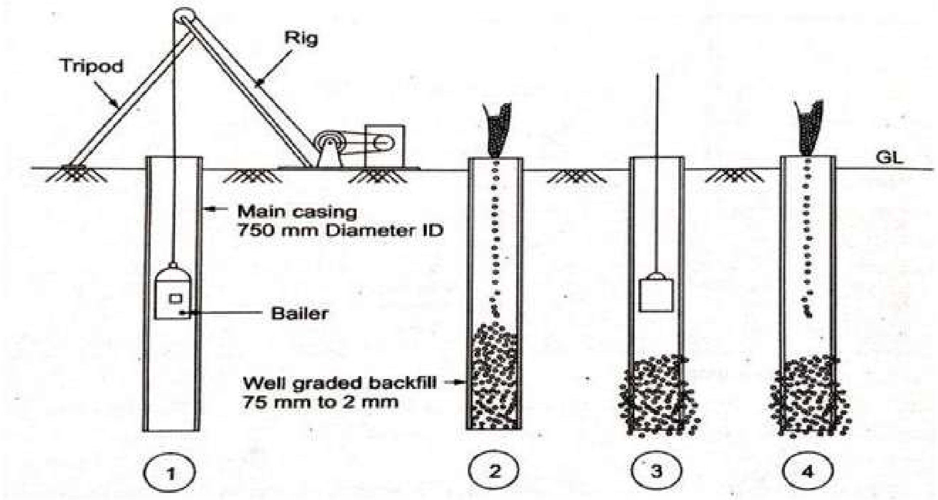


Fig. 2.2 Installation of the granular column by rammed granular column method (Datye and Nagaraju 1975).

2.2.2.2 Displacement Method

The displacement method involves laterally pushing the soil outward to form a borehole without removing it. A vibratory probe is used to penetrate the ground, simultaneously introducing and compacting granular material. Unlike the non-displacement method, this technique results in the densification of the surrounding soil, thereby improving its load-bearing properties.

Two of the most commonly adopted displacement-based techniques are:

- **Vibro Replacement**
- **Vibro Displacement**

These methods are particularly effective for enhancing the performance of granular columns in loose or soft soils by increasing both the column and surrounding soil strength.

2.2.2.2.1 Vibro replacement method

Wet top feed method

The wet top feed method is a vibro replacement technique primarily used to improve cohesive soils that contain more than 20% fines and exhibit an undrained shear strength (S_u) between 15 and 35 kPa. This method is particularly suitable for ground improvement projects located below the water table, where traditional dry methods may not be effective (McCabe et al. 2009; Moseley and Kirsch 2004). The procedure of the wet top feed method is:

- A vibrofloat is inserted into the ground and advanced to the required depth by jetting water, which loosens and displaces the soil, forming a borehole.
- Once the desired depth is reached, granular material is introduced from the surface and carried downward by a continuous upward flow of water.
- The water facilitates even distribution and aids in compacting the backfill material effectively within the formed cavity.
- As the vibrofloat is gradually withdrawn—typically in 0.5-meter intervals—compaction occurs in stages from the bottom up.
- The water jet not only assists in material placement but also stabilizes the borehole walls, preventing the collapse of the surrounding soil and ensuring uniform column formation.

Fig. 2.3 illustrates the schematic sequence of the wet top feed method in the field. This method typically achieves effective treatment within a depth range of 5 to 15 meters. The formation of end-bearing granular columns is often preferred in this system, as it enhances load transfer capacity to the firmer stratum below (Barksdale and Bachus

1983). One of the main drawbacks of the wet top feed method is its high-water demand, which can raise environmental and logistical concerns. The large volume of water used must be carefully managed, treated, and disposed of to prevent soil or groundwater contamination and comply with environmental regulations.

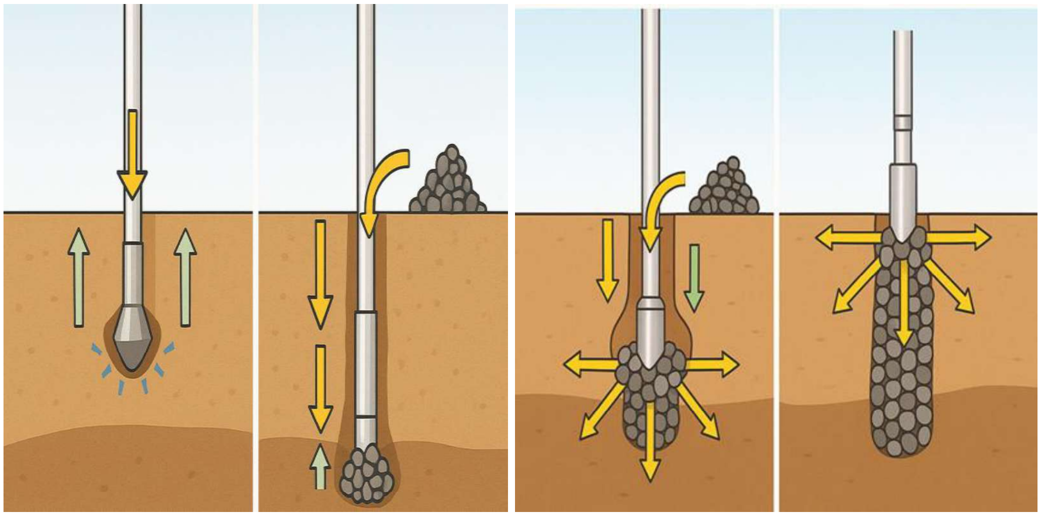


Fig. 2.3 Wet top feed method (Reference: (Mokhtari and Kalantar 2012).

2.2.2.2.2 Vibro displacement method (dry method)

The vibro displacement method, commonly referred to as the dry method, is an effective ground improvement technique used for installing granular columns without relying on water. This approach is particularly valuable in environments where water usage is restricted or environmentally sensitive. Two primary variants of this method are employed based on soil characteristics: the dry top-feed method and the dry bottom-feed method.

Dry top feed method:

The dry top-feed method is best suited for stable, stiff soils with an undrained shear strength exceeding 30 kPa. In this approach, granular material is introduced into the borehole from the ground surface without the assistance of a continuous water jet. The installation process generally mirrors that of the wet top-feed method, with the vibro probe penetrating to the required depth and gradually being withdrawn in stages as the material is placed and compacted. Fig. 2.4 illustrates the schematic of the dry top-feed method. This method is favored for its operational simplicity, especially in projects involving shallow to medium treatment depths and where the use of water is either impractical or undesirable due to environmental or logistical constraints.

However, the dry top-feed method presents significant limitations when applied to soft clay soils. These soils often lack sufficient lateral support, and without the continuous presence of the vibro probe during withdrawal, there is a high risk of borehole collapse, which can compromise the integrity of the installed columns. As a result, this method is not recommended for use in soft ground conditions (McCabe et al. 2009; Mckelvey et al. 2004). Typically, granular columns constructed using this method have diameters ranging from 0.4 to 0.8 meters and lengths between 10 and 15 meters.

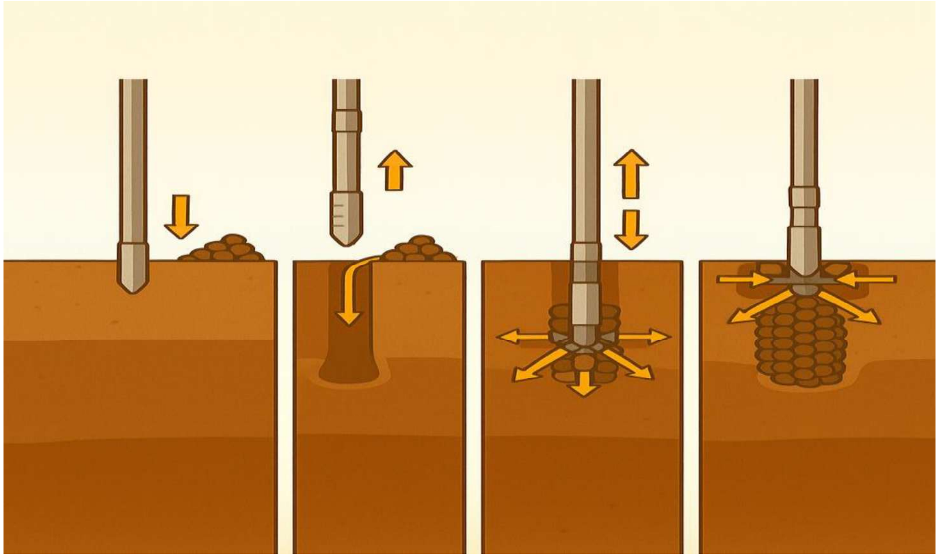


Fig. 2.4 Dry top feed method (Mokhtari and Kalantar 2012).

Dry bottom feed method:

This method was first introduced in the UK during the 1980s and has become the most common technique for the installation of granular columns (McCabe et al., 2009). This technique is mostly suitable for very soft and soft soil with an undrained shear strength ranging from 15 to 50 kPa. This method does not require continuous water flow, as compared to the wet method. Rather, a pipe is connected to the vibrofloat, which remains in the bore throughout installation and delivers granular material directly to the bottom of the borehole. The vibrofloat adds stability and guards against soil collapse or contamination from nearby materials. When using water is impractical or not allowed, particularly in environmentally sensitive places, the dry bottom-feed approach is recommended. When compared to water-based methods, it provides a cleaner and more controlled installation procedure. The granular material is fed into the pipe from a hopper at the surface, guaranteeing precise and consistent delivery to the desired depth. Typically, the diameter of the granular columns ranges from 0.4 to 0.8 meters, and the length can be up to 15 meters (McKelvey et al., 2004). The step-by-step installation process of this technique is presented in Fig. 2.5.

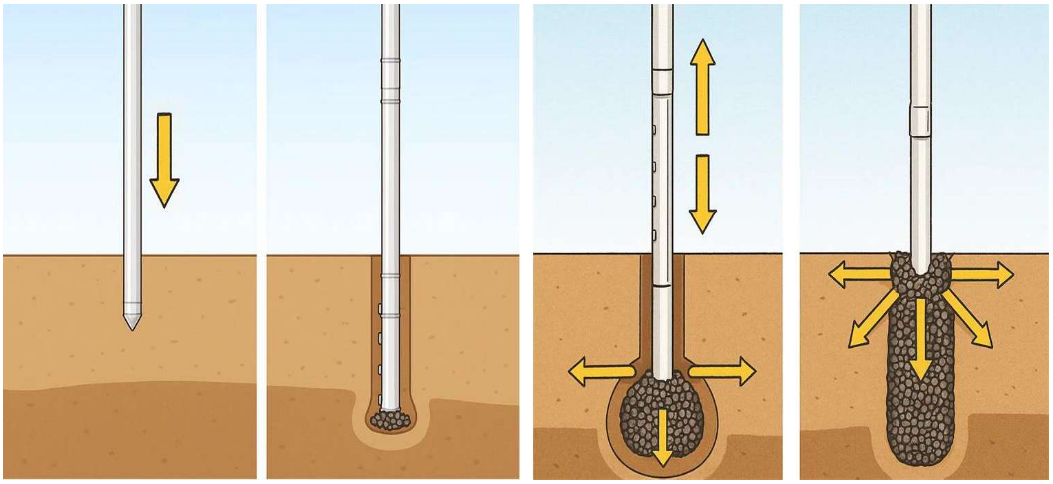
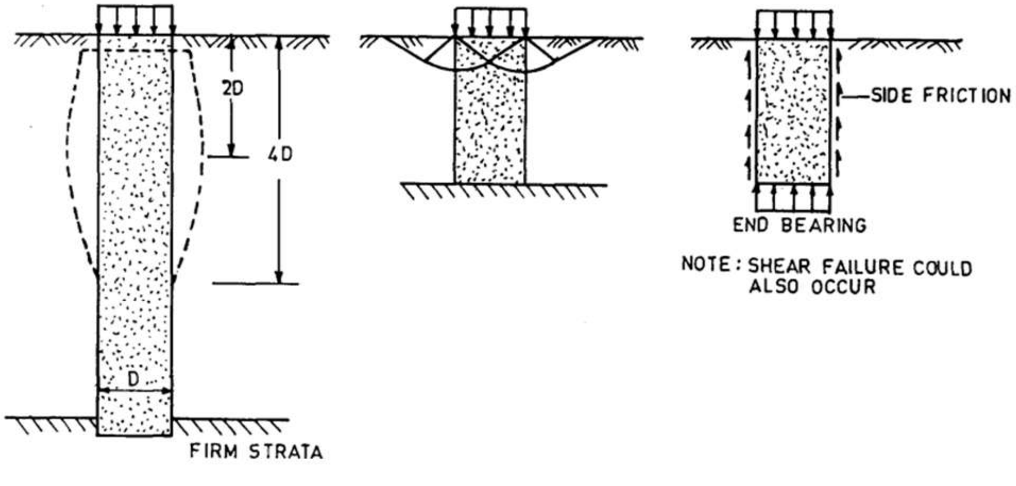


Fig. 2.5 Dry bottom feed method (Reference: (Mokhtari and Kalantar 2012)).

2.2.3 Granular column failure mechanisms

Granular columns are typically constructed in two configurations: end-bearing, where the column rests on a firm underlying stratum beneath the soft soil, and floating, where the column's base remains embedded within the soft soil layer. The mode of failure for a single granular column, when subjected to axial loading over its plan area, is largely dependent on its length. As noted by Barksdale and Bachus (1983) and outlined in (IS 15284-(Part 1) 2003) granular columns with lengths exceeding a critical threshold—generally about four times the diameter of the column—are most likely to fail by bulging regardless of whether they are end-bearing or floating (Fig. 2.6a). For columns shorter than the critical length, the failure mode differs based on the type of support. End-bearing columns resting on a rigid base are prone to general shear failure (Fig. 2.6b) while floating columns are more susceptible to punching failure (Fig. 2.6c).

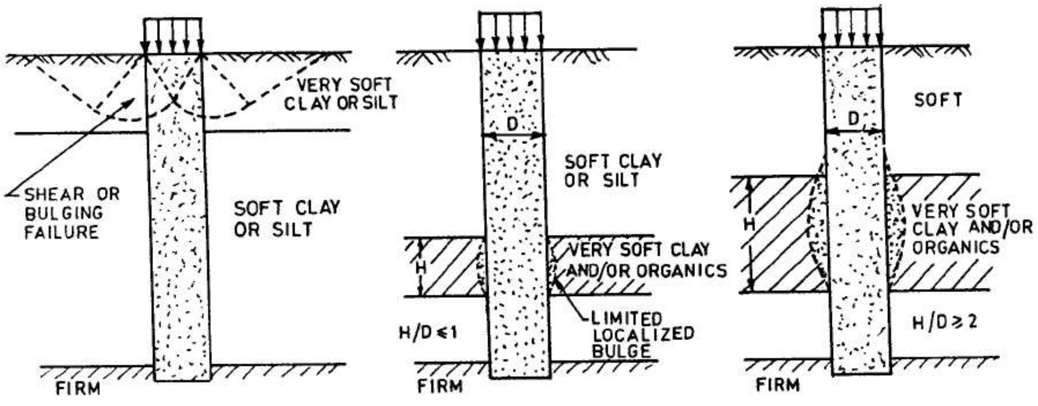


(a) **(b)** **(c)**

Fig. 2.6 Failure mechanisms of a single granular column in a homogeneous soft layer according to (Barksdale and Bachus 1983; IS:15284 (Part 1) 2003), (a) Long granular column with end-bearing or floating support-Bulging failure (b) Short granular column with rigid base-Shear failure, (c) Short floating granular column- Punching failure.

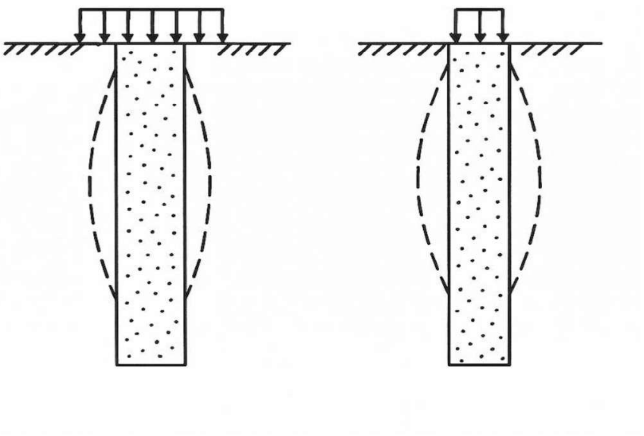
These failure patterns are typical in homogeneous or uniform soils. However, in practical applications, soils are often non-uniform and may contain isolated areas of very soft, cohesive soils, which can result in significant bulging occurring at both shallow and deep levels. The Indian Standard IS 15284 (Part 1) 2003 provides a recommended failure pattern for such non-uniform soil conditions, as illustrated in Fig. 2.7.

In real-world field scenarios, the load is typically distributed over a larger area encompassing both the granular column and the surrounding soil (Fig. 2.8). This shared load distribution reduces the extent of bulging and contributes to a higher ultimate load-bearing capacity and less settlement of the ground. The load distribution behavior between the granular column and the adjacent soil significantly enhances the performance of the ground improvement system (IS: 15284 (Part 1) 2003).



(a) (b) (c)

Fig. 2.7 Failure mechanisms of a single granular column in a non-homogeneous soft layer according to (IS:15284 (Part 1) 2003), (a) Soft layer at the surface-bulging or shear failure, (b) Thin very soft layer- contained local bulge, (c) Thick very soft layer-local bulging failure.



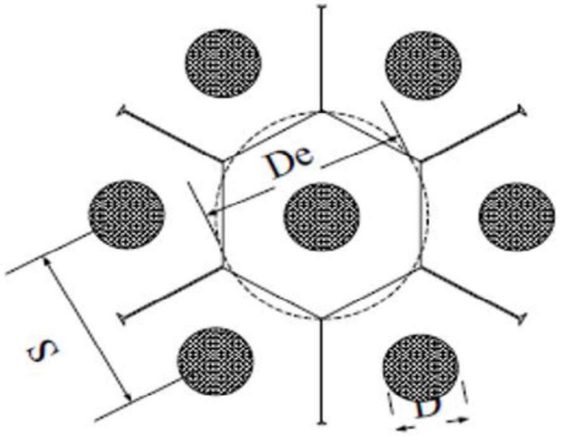
(a) (b)

Fig. 2.8 Different types of static loadings applied to granular columns: (a) area loading, (b) column loading (IS: 15284 (Part 1) 2003).

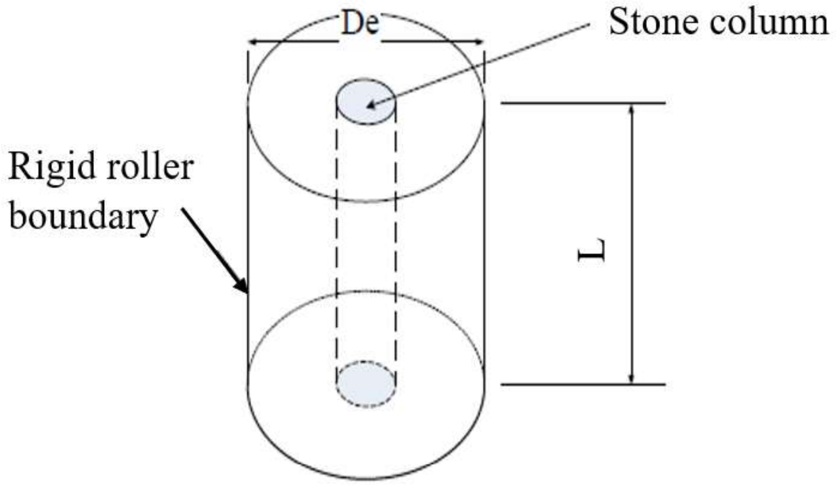
2.2.4 Basic relationships

In practical foundation design, especially for large infrastructure projects supported by multiple granular columns, settlement and stability analyses are commonly carried out using the concept of a tributary area around each column, as shown in Fig. 2.9. This tributary area, which depends on the spacing between adjacent columns, typically forms a regular hexagonal shape surrounding each granular column. However, for simplification in analysis, this hexagonal area is often approximated by an equivalent circular area with the same total size, characterized by an effective diameter (D_e).

This circular region, containing both the granular column and the surrounding soil, forms what is known as the unit cell. Within this configuration, the granular column is positioned concentrically inside the unit cell boundary. The boundary conditions applied to this unit cell model—used for analytical or numerical assessment—are outlined in Fig. 2.9, providing a framework for evaluating load distribution, settlement, and overall stability.



Stone column in a group



Unit cell

Fig. 2.9 Unit cell idealization (Barksdale and Bachus 1983).

Three typical arrangements of granular columns—triangular, square, and hexagonal—are shown in Fig. 2.10. Among these, the triangular pattern provides the densest packing for a given column spacing, making it the most efficient configuration in terms of spatial utilization. Some fundamental relationships, assuming the unit cell concept (FHWA 1983), are as follows:

(i) Equivalent Diameter (D_e)

To simplify the analysis, the unit cell concept is applied, where the area surrounding a granular column is approximated as a circle with an effective diameter D_e. This approximation allows for straightforward calculations based on column spacing s. According to FHWA (1983), De varies with the pattern as follows:

For an equilateral triangular pattern of granular columns, the equivalent circle has an effective diameter D_e as given below:

$$D_e = 1.05s \tag{2.1}$$

For a square grid pattern,

$$D_e = 1.13s \tag{2.2}$$

For a hexagonal grid pattern,

$$D_e = 1.29s \tag{2.3}$$

where s is the spacing of granular columns

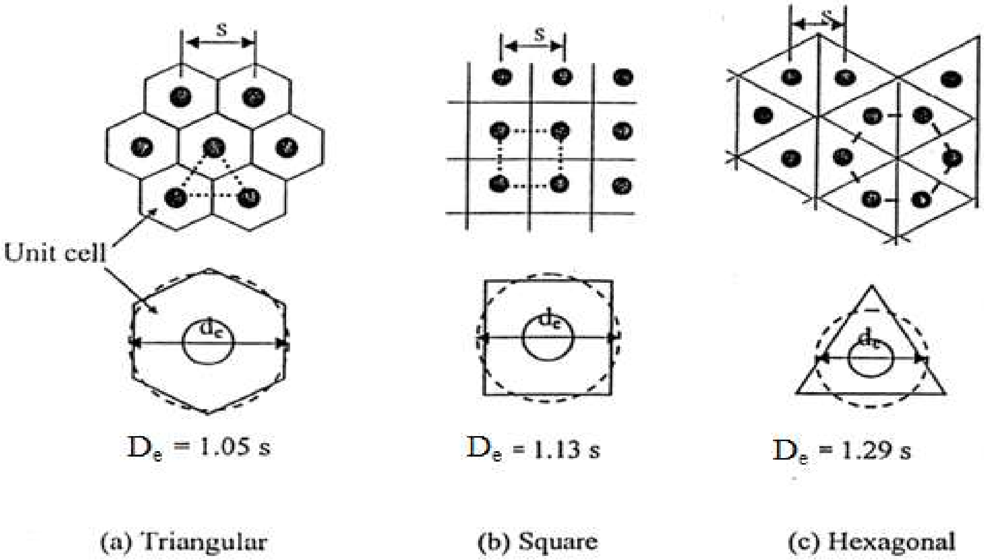


Fig. 2.10 Typical granular column arrangements.

(ii) Area replacement ratio (A_r)

The volume of soil replaced by granular columns 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 column replaced by the granular materials.

$$A_r = A_{GC}/A \tag{2.4}$$

where A_{GC} is the area of the granular column after compaction, and A is the total area within the unit cell. Further, the ratio of the area of the soil remaining to the total area is then

$$a_c = A_s/A \tag{2.5}$$

$$= 1-A_r$$

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

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

Where d is the diameter of the compacted granular column, s is the center-to-center spacing of the granular columns, and C_1 is a constant dependent upon the pattern of granular columns 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 columns, the area replacement ratio is then

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

(iii) Stress Concentration Ratio

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

$$n = \frac{\sigma_{GC}}{\sigma_S} \tag{2.8}$$

where σ_{GC} is the stress in the granular column, and σ_s 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:

$$\sigma = \sigma_s A_r + \sigma_{GC} (1 - A_r) \tag{2.9}$$

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

$$\sigma_C = \frac{\sigma}{[1+(n-1)A_r]} = \mu_C \sigma \tag{2.10}$$

and

$$\sigma_S = \frac{n\sigma}{[1+(n-1)A_r]} = \mu_S \sigma \tag{2.11}$$

where μ_c and μ_s are the ratios of stresses in the soft soil bed and granular column, respectively, to the average stress σ over the tributary area. For specific field conditions, the stresses in both the granular column and the surrounding soft soil can be effectively estimated using Equations (2.10) and (2.11), provided that a reasonable value of the stress concentration ratio (n) is assumed based on prior experimental observations. These equations are particularly useful for evaluating settlement and stability in ground improvement projects involving granular columns. Field studies have indicated that the value of the stress concentration factor typically ranges between 2 and 5, as reported by (Goughnour and Bayuk 1979; Vautrain 1977)

2.3 Geosynthetics

(a) Materials

Geosynthetics are mostly made from plastic-based materials (polymers) derived from hydrocarbons. Sometimes, materials like fiberglass, rubber, or natural fibers are also used. These materials are popular in civil engineering fields such as transportation, geotechnical, environmental, and hydraulic engineering. The most commonly used polymers for geosynthetics (Koerner 2005) include:

1. High-Density Polyethylene (HDPE)
2. Linear Low-Density Polyethylene (LLDPE)
3. Polypropylene (PP)
4. Polyvinyl Chloride (PVC)
5. Polyester (PET)
6. Expanded Polystyrene (EPS)
7. Chlorosulphonated Polyethylene (CSPE)
8. Ethylene Propylene Diene Monomer (EPDM – a thermoset rubber)

(b) Functions of Geosynthetics

Geosynthetics serves five major engineering functions:

1. **Separation**: Keeps different soil layers from mixing. For example, a geotextile between soft subgrade and ballast in a railway track keeps them separate.
2. **Reinforcement**: Strengthens the soil by providing tensile resistance, such as using geogrids beneath embankments or retaining walls.

3. **Filtration**: Allows water to pass through while holding back soil particles. For instance, geotextiles are used around drainage layers instead of sand filters.
4. **Drainage**: Helps remove excess water from soil, like geonets behind retaining walls or in dams.
5. **Containment**: Acts as a barrier to prevent fluid or gas movement. Geomembranes in landfills or water canals serve this role.

These functions make geosynthetics both efficient (long-lasting and low maintenance) and cost-effective compared to traditional methods.

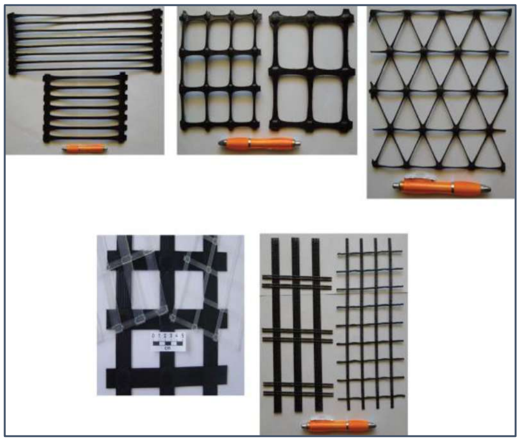
(c) Types of Geosynthetics

There are several types of geosynthetics, each designed for specific applications, as shown in Fig. 2.11:

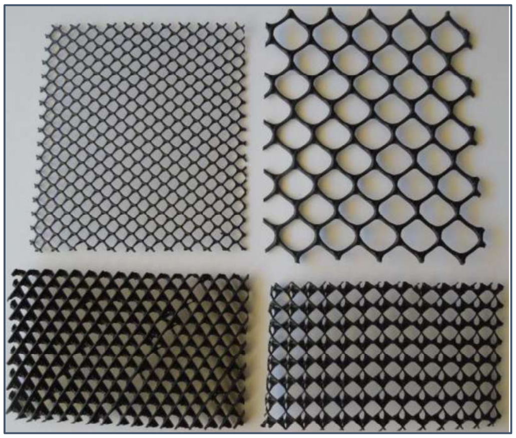
1. **Geotextiles**: Fabric-like materials made of synthetic fibers (mainly polypropylene). They can filter, drain, separate, and reinforce.
2. **Geogrids**: Grid-like materials with large openings. Used only for **reinforcement** of weak soils or waste materials. HDPE is common in one-direction grids PP in two-direction grids.
3. **Geonets**: Net-shaped materials used for drainage. Made from polyethylene, they transport fluids within soil layers.
4. **Geomembranes**: Waterproof sheets used for containment. Commonly made from PE or PP, used in lining reservoirs, canals, and landfills.

5. **Geosynthetic Clay Liners (GCLs)**: Prefabricated layers of bentonite clay placed between geotextiles or geomembranes to improve containment. Often used under geomembranes in landfills.
6. **Geofoam**: Lightweight blocks made from expanded polymers (like EPS). Used as lightweight fill-in embankments or to reduce loads on weak soils.

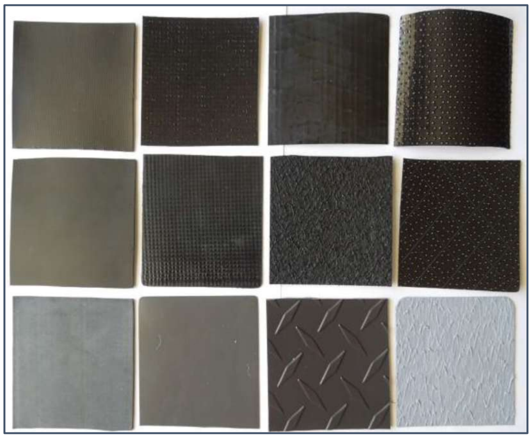
Geotextiles



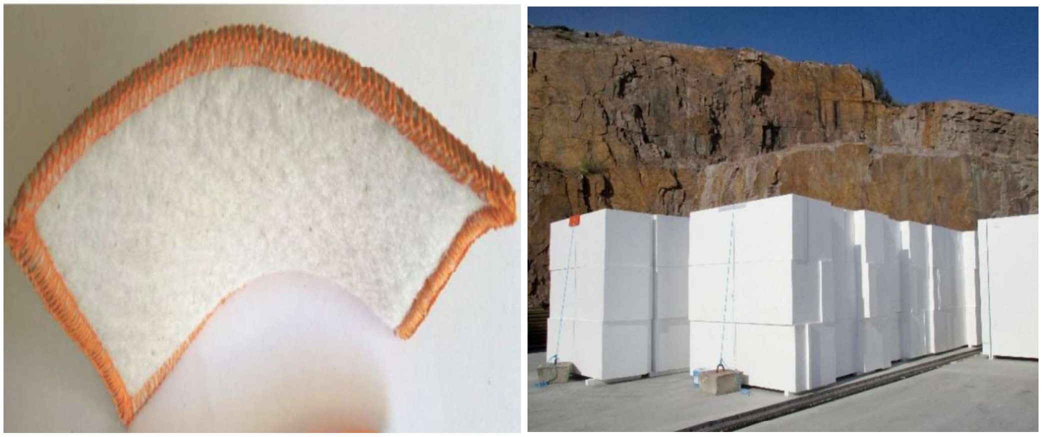
Geogrids



Geonets



Geomembranes



GCL Geofoams

Fig. 2.11 Different types of geosynthetics (Shukla 2016).

2.4 Literature review

2.4.1 Analytical studies

Several studies done in the past have covered the analytical methods adopted to establish the design procedure for the use of granular columns in the improvement of soft soils. The methods elaborated in the literature focussed on the performance evaluation of granular columns in terms of the ultimate bearing capacity of ordinary and encased granular columns, load-settlement behavior, and efficiency of the granular columns. The effect of geosynthetic reinforcement in the performance improvement of granular columns was also factored in the design approaches developed over time.

Greenwood (1970) proposed a design approach for improving the bearing capacity and reducing settlement in soft clays reinforced with granular columns. The improvement depends on the lateral support provided by the surrounding clay, the column diameter, and the degree of compaction. When the load is applied via a spread footing, it is concentrated on the granular column, causing it to expand and exert lateral stresses on the surrounding soil. The lateral stresses were resisted by the passive pressure of the clay, making the column behave like it is in a triaxial chamber. Failure mechanisms include local shear failure in the surrounding clay or end-bearing failure at the column's base. Field observations showed that gravel columns reduced settlement by 50%, while sand columns reduced settlement by 15% compared to untreated soil. This approach emphasizes the role of lateral support and column properties in enhancing soil performance.

Hughes et al. (1975) developed a design approach for stone columns on soft ground, emphasizing their behavior under applied loads. They noted that as the column expands, the radial resistance of the surrounding soil reaches a limiting value, leading to indefinite expansion. Stone columns were modeled as behaving like a column in a triaxial chamber with limited cell pressure. They proposed an expression to calculate the maximum vertical stress the column can carry, incorporating factors such as undrained strength (c), pore water pressure (u), internal friction angle of the column material (ϕ'), and initial radial stress in the soil (σ_{ro}).

$$q_{ult} = \frac{(1 + \sin\phi')}{(1 - \sin\phi')}\,(\sigma_{ro} - u + 4c) \tag{2.12}$$

The study concluded that increasing the column length beyond a depth-to-diameter ratio of 6.3 does not significantly enhance load-carrying capacity. Additionally, it was observed that applied loads consolidate the surrounding clay, increasing radial stiffness but not significantly adding to the column's strength. This approach highlights the importance of soil-column interaction and the limitations of column length in practical applications.

Brauns (1978) proposed a design approach for modeling single isolated columns in soft clays using an undrained triaxial passive pressure distribution. The study assumed that the upper portion of the pier behaves like a cohesionless cylindrical triaxial test specimen, developing shear planes inclined at an angle of $\delta p = (45° + \phi'/2)$. Brauns derived an expression for the maximum vertical stress on the pier, accounting for surcharge effects and undrained shear strength of the clay.

$$q_{ult} = \left(q + \frac{2c}{sin\,2\delta}\right)\left(1 + \frac{\tan\delta p}{\tan\delta}\right)\left(q + \frac{2c}{sin\,2\delta}\right)\tan^2\delta p \qquad (2.13)$$

where q was the surcharge, c was the undrained shear strength, and δ is the angle of the shear plane. This approach emphasizes the role of passive resistance and shear plane mechanics in determining the load-carrying capacity of granular columns.

(Barksdale and Bachus 1983) developed a design approach for estimating the bearing capacity of strip and square footings supported by groups of granular columns. The study used the unit cell idealization to represent finite groups of columns and assumed a bilinear failure surface. The resistance along the failure surface was calculated using average shear strength parameters, including friction angle and cohesion, which were adjusted based on the stress concentration factor and area replacement ratio. For strip footings, classical earth pressure theory was applied to approximate confining stress, while cylindrical cavity expansion theory was used for square foundations. The bearing capacity of the group was determined by combining confining stress and shear resistance along the failure surface.

$$q_{ult} = \sigma_3 \tan^2\left(45 + \frac{\phi avg}{2}\right) + 2\, c_{ang} \tan\left(45 + \frac{\phi avg}{2}\right) \qquad (2.14)$$

$$\phi_{avg} = \tan^{-1}(n\, a_r * \tan\phi') \qquad (2.15)$$

$$c_{ang} = (1 - a_r)\, c \qquad (2.16)$$

where σ_3 is the confining stress; ϕ_{avg} is the average internal friction angle; c_{ang} is the average cohesion; n is the stress concentration ratio. This approach highlights the importance of stress distribution, area replacement ratio (a_r), and soil-pier interaction in predicting the load-carrying capacity of aggregate pier groups.

Priebe (1995) provided a design method to evaluate the improvement in mechanical properties of soft clays reinforced with stone columns. The work assumed that the column rests on a hard layer, the column material is incompressible, and the bulk density of the column and soil is negligible. Priebe modeled the column's behavior as shearing from the start while the surrounding clay reacted elastically. He introduced the basic improvement factor, which accounts for the modulus of elasticity of the composite material, the area replacement ratio, and the lateral earth pressure coefficient.

$$no = 1 + \frac{Ac}{A}\left(\frac{\left(5-\frac{Ac}{A}\right)}{4\,Kac\left(1-\frac{Ac}{A}\right)} - 1\right) \tag{2.17}$$

Where A_c is the area of the column, A is the area of the unit cell $K_{ac} = \tan^2\left(45 + \frac{\phi avg}{2}\right)$

Priebe also defined a load distribution factor to estimate the portion of the load carried by the column. Adjustments were made to avoid overestimating column resistance, and the composite's shear strength parameters were calculated based on the load distribution factor. This method provides a systematic approach to predict the load-sharing and stiffness improvement in clay reinforced with stone columns.

Watts et al. (2000) presented a design approach for stone columns, focusing on their behavior under yielding shear (bulging failure). The work modified the equation by Hughes and Withers (1975) to account for the passive earth pressure coefficient (K_{pc}) of the column material and the pore pressure conditions. The approach assumes that granular fill around the column increases radial stresses during construction, creating an improved zone with a diameter of 1.5 times the column diameter.

$$q_{ult} = K_{pc}\ [\ K_0\ (\gamma_{sh} - u_{so}) + u_{so} - u_s + 4\ c_u\ ] \tag{2.18}$$

Where, u_{so} is the initial pore water pressure at a depth h,

Watts et al. adapted the method to predict stress distribution between the column and surrounding soil proposed by Baumann and Bauer (1974), incorporating the improved zone's effects. The findings showed that bulging typically occurs at a depth of three times the column diameter below the top, and the load carried by the columns was smaller than predicted by earlier methods. This approach emphasizes the importance of radial stress enhancement and improved zones in determining column performance.

Murugesan and Rajagopal (2010) developed a step-by-step design approach for geosynthetic-encased stone columns, focusing on their load-carrying capacity and confinement effects. The method assumes that the applied foundation pressure is fully carried by the stone column, and the load is calculated based on the unit cell area. The limiting stress on a non-encased column (σ_v) is determined using the passive pressure coefficient (K_{pc}) and the undrained cohesion of the surrounding clay (c_u).

$$\sigma_v = K_{pc} \left[\sigma_{ro} + 4\, c_u \right] \tag{2.19}$$

Additional confinement required for encased columns is calculated, and the corresponding hoop tension in the encasement is estimated. The hoop strain is evaluated based on permissible settlement, and a suitable geosynthetic material is selected to provide the required tensile strength at the calculated strain level. This approach highlights the role of geosynthetic encasement in enhancing column performance by reducing bulging and increasing lateral confinement.

2.4.2 Granular columns under static loading

Wood et al. (2000) performed laboratory model tests on clay beds reinforced with granular columns subjected to surface footing loading. The deformed shapes of the granular column were obtained using an exhumation technique to deduce how the columns transferred load to the surrounding clay. The effect of change in diameter, length, and spacing of the model granular columns was determined. To study the contact stress distribution between the columns and the surrounding clay at different loading stages of the footing, pressure transducers were used. It was found that the middle columns under the footing are typically the most heavily loaded, as shown in Fig. 2.12.

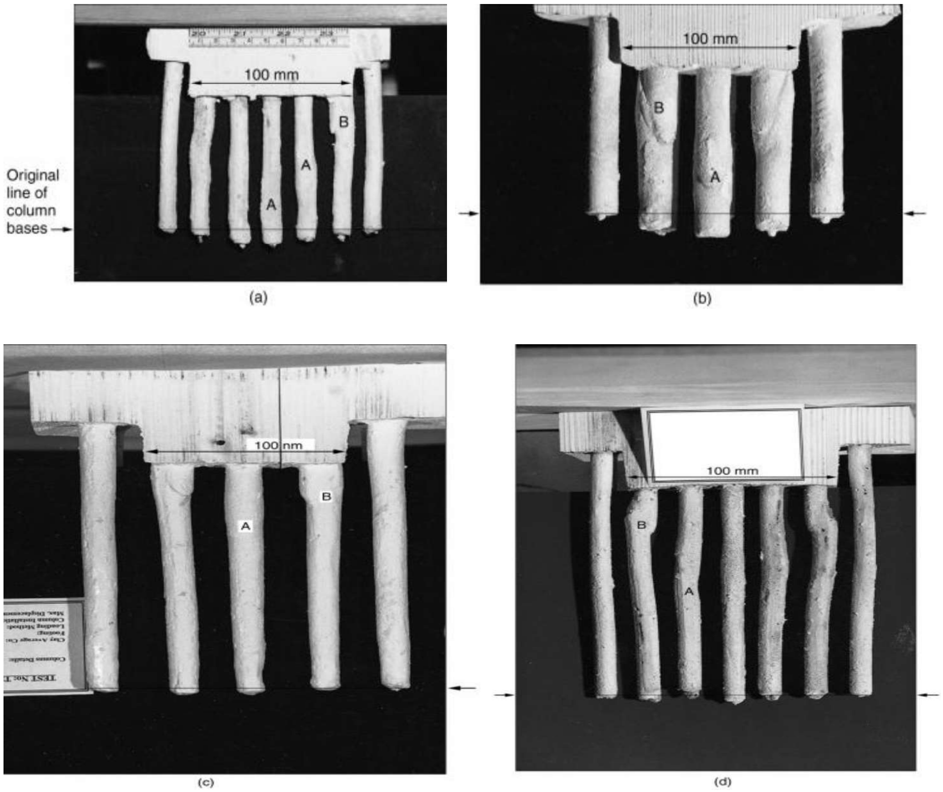


Fig. 2.12 Deformed sand columns exhumed at the end of footing penetration. (Wood et al. 2000)

Ambily and Gandhi (2007) studied the behavior of a single column and a group of seven columns carried out by varying parameters like spacing between the columns, shear strength of soft clay, and loading conditions by performing laboratory model tests on soft clay with different shear strength, reinforced with 100 mm diameter column. The tests were carried out either with an entire equivalent area loaded to estimate the stiffness of improved ground or only a column loaded to estimate the limiting axial capacity. Pressure cells were fixed in the loading plate during the group experiments to quantify actual stress on the clay and column. Good agreement was obtained between the experimental and numerical results from the FEM. Significant improvement is not achieved when columns are spaced more than three times their diameter apart.

Gniel and Bouazza (2009) performed a series of small-scale model tests to study the behavior of geogrid-encased granular columns. The study analyzed the effect of variation in the length of geogrid encasement and investigated how the partial geogrid encasement behaves as compared to the full geogrid encasement. Also, the single-column behavior was compared with the group-column behavior. It was found that partially encased granular columns had a steady reduction in vertical strain with the increase in encasement length for both single and group columns. Radial column bulging was observed directly below the base of the encasement. In the case of the group column, the increase in length of encasement resulted in an increase in column stiffness and steadily reduced vertical strain. The vertical strain was reduced by 80% for fully encased columns as compared to only clay beds without reinforcement.

Murugesan and Rajagopal (2010) investigated the performance of both single and grouped granular columns with and without geosynthetic-encasement for improving soft ground conditions. Laboratory tests were performed in a large-scale testing tank to study the improvement in the load-bearing capacity of granular columns installed in clay beds prepared in controlled conditions. An improvement in load capacity and stiffness was observed due to the encasement of the granular column. The ordinary granular column exhibits a softer response with significant strain softening, whereas the geosynthetic encased granular column does not exhibit a significant strain softening response beyond the peak load. It was observed that the load capacity depends on the modulus of the encasement and the diameter of the granular column. Also, the higher stress concentration ratio was obtained for the encased granular column and it increased with an increase in the modulus of the encasement. Additionally, a design chart was provided to aid in selecting appropriate geosynthetic-encased granular columns and estimating the necessary tensile strength of the encasement material for a given applied pressure.

Shahu and Reddy (2011) performed load-controlled, fully drained laboratory model tests on well-instrumented small-scale models of floating granular column group foundations in soft clayey soil beds with known effective stress states. The effect of area ratio, relative density, moisture content of the column material, and length of columns was studied. The area ratio, normalized column length, over consolidation ratio, relative stiffness, and stress ratio of the clayey soil were the major parameters, and the thickness of the mat, in addition to the dilation angle and angle of shearing resistance of granular material, are the minor parameters affecting the response of a group of floating stone column foundations. It was observed that the bending of a column depends on the position of the column in the group. The bending increased from the center column to a peripheral column and to a corner column.

Dash and Bora (2013) investigated the improvement in the performance of soft clay foundations using a combination of granular columns and geocell sand mattresses as reinforcement. The effects of granular column length, column spacing, and the height of the geocell mattress on the bearing capacity and settlement behavior of the soft soil foundation were studied through laboratory model tests. It was found that the bearing capacity increased by 3.7 times while using only granular column whereas with the use of both granular column and geocell reinforcement resulted in 10.2 times increase in the bearing capacity of the composite foundation. An optimum column length of 5 times the diameter and a spacing of 2.5 times the diameter was reported in the study. Geocell mattress of a height equal to the footing diameter was reported to provide the best result against footing settlement.

Ali et al. (2014) investigated the effectiveness of geosynthetic encased granular columns in improving the performance of soft soil. The use of two different geosynthetic reinforcements was done in the study; one was in the form of vertical geosynthetic encasement and the other was in the form of circular horizontal geosynthetic discs within the columns. Model tests were performed on the single and group of granular columns 30 mm in diameter. The columns were installed in both end-bearing and floating configurations, and load tests were performed to evaluate the improvement in the bearing capacity of the reinforced soil mass. It was reported that the geosynthetic encasement significantly improves the column performance, which was attributed to the mobilized hoop stresses in the geosynthetic material. The use of geogrid encasement was found to be more effective for end-bearing columns and geotextile was more effective for floating columns. The group columns exhibited lower failure stresses compared to single columns, as the columns in the group pattern were subjected to combined compression and bending, whereas the single column was subjected to pure compression (Fig. 2.13).

Fattah et al. (2016) conducted laboratory model tests to study the behavior of embankments constructed on soft clay reinforced with ordinary granular columns and geogrid-encased granular columns. The tests performed evaluated the effect of column spacing, length-to-diameter ratio (*l/d*), and height of the embankment on the bearing capacity, settlement of the embankment, and stress distribution. The geogrid-encased granular columns significantly enhanced the bearing capacity of the soil compared to ordinary granular columns. A higher improvement ratio was observed for lower column spacings (s = 2.5d). The higher settlement reduction ratios were reported for encased granular columns at smaller spacing and lower heights of the embankments. Local shear failure was observed in untreated soil, while the reinforced soil exhibited general shear failure.

(a) (b) (c) (d)

Fig. 2.13 Deformed shapes of fully geosynthetic-encased floating stone columns: (a) geotextile-encased column group; (b) geogrid-encased column group; (c) geotextile-encased single column; (d) geogrid-encased single column (Ali et al. 2014).

Debnath and Dey (2017) studied the behavior of geogrid-reinforced sand beds and unreinforced sand beds overlying granular column-reinforced soft clay foundations. It was observed that in comparison to unreinforced clay bed, the bearing capacity of the geosynthetic reinforced clay bed was 1.72 times, granular columns with unreinforced sand bed were 2.83 times, and granular columns with geogrid reinforced sand bed were 5.3 times. The critical thickness of the unreinforced soil bed was found to be 0.3 times the footing diameter, whereas, for the geogrid reinforced sand bed, it was 0.2 times the footing diameter. The use of geogrid reinforced sand bed was reported to reduce the bulging in the columns and resulted in increased depth of deformation in granular columns. The ideal length-to-diameter ratio for granular columns with geogrid reinforced sand bed was reported to be 6. Higher geogrid stiffness was observed to provide higher improvement in the bearing capacity of the foundation.

Ghazavi et al. (2018) investigated the use of vertical and horizontal reinforcement in granular columns to improve the stability of soft soils (Fig. 2.14). Horizontal reinforced granular columns use geosynthetic material in horizontal layers to reinforce the columns. This helps in reducing lateral bulging and increases the load-bearing capacity. Horizontally reinforced granular columns are more effective with higher stiffness reinforcement materials, longer column lengths, and smaller spacing between the horizontal reinforcement layers. Geogrid reinforcement is found to be more effective than geotextile due to better interlocking between the geogrid material and aggregates. It was reported that horizontal reinforcement is better than vertical reinforcement in improving the bearing capacity of soft soils, especially for larger column diameters. The optimum spacing of the horizontal reinforcement layers was reported to be 0.25 times the column diameter.

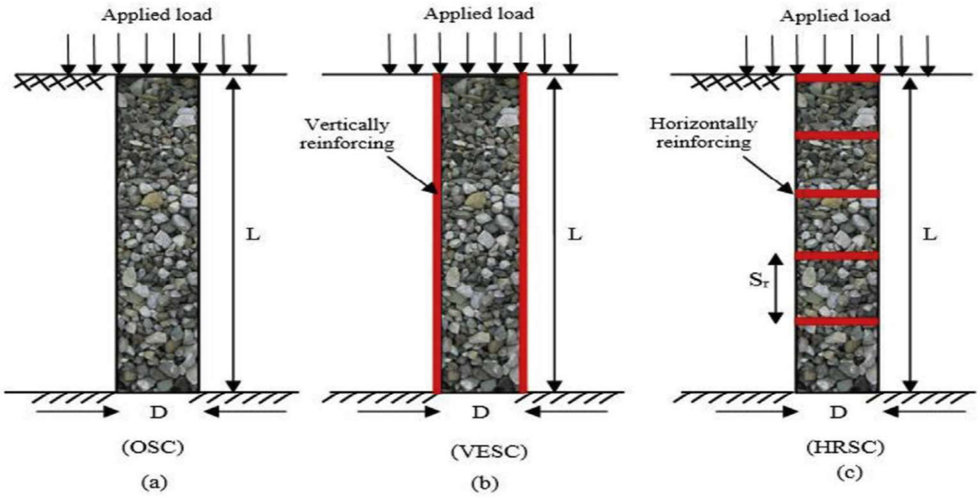


Fig. 2.14 Schematic diagrams of: (a) Ordinary granular column; (b) Vertically encased granular column; (c) Horizontally reinforced granular column. (Ghazavi et al. 2018).

2.4.3 Granular columns under cyclic loading

Granular columns are widely used to support a variety of foundation types across different soil conditions, particularly in large-scale infrastructure projects such as airports, railways, and road embankments, where dynamic loading is a significant concern. These columns are especially effective in reducing the risk of liquefaction during earthquakes by increasing the density of the surrounding soil and enhancing drainage, which helps in controlling the build-up of pore water pressure beneath the foundation. In addition to improving drainage and stability, granular columns also increase the overall load-bearing capacity of the foundation system while reducing the stress imposed on the adjacent soft soils. Despite their widespread use, there has been limited research focusing on the behavior of granular column-reinforced soft soil foundations under cyclic loading conditions. The key studies available in the literature addressing the performance of such improved foundations under repeated or cyclic loading are summarized below.

Cengiz and Güler (2018) investigated the seismic and post-seismic behavior of geosynthetic encased granular columns and ordinary granular columns through 1-g shake table tests. It was observed that columns with higher stiffness geotextile exhibited uniform distribution while columns with lower stiffness geotextile experienced localized bulging. A linear relationship was observed between seismic energy input and strain in the reinforcement.

Yoo and Abbas (2019) performed vertical cyclic loading tests on the soft clay improved with encased granular columns to simulate traffic or train-induced stresses. It was found that geosynthetic encasement significantly reduces settlement, cyclic degradation, and excess pore water pressure compared to ordinary granular columns; greater benefits were reported under cyclic loadings than static loading. A higher stress concentration ratio was reported under static loading compared to cyclic loading conditions.

Aqoub et al. (2020) studied the behavior of shallow reinforced and reinforced piled embankments of varying heights under static and multi-stage cyclic loading conditions through laboratory experiments. It was found that soil arching improves with an increase in the height of the embankment under static loading stages, but it weakens initially under cyclic loading, and then it recovers with an increase in the number of cycles. The provision of multiple enforcement layers enhances the loading capacity of the piles, reduces settlement, and stabilizes soil arching. However, the improvement diminishes with the increase in the height of the embankment. It was observed that more than 50% of the settlement occurs during the first cyclic loading stage.

Gao et al. (2021) studied the behavior of geosynthetic encased stone columns under cyclic loading in soft soil foundations. A scaled model test setup (1:40) was used to represent an encased granular column with a diameter of 800mm. Model tests were conducted to examine the effect of parameters such as the length-to-diameter ratio strength of the wrapping material on the performance of reinforced soil foundations. Cyclic loading was applied using a sinusoidal load form with 1 Hz frequency and 1500 number of load cycles. The use of encased granular columns enhances the stress ratio in the columns, with more load being transferred to the granular columns as the l/d ratio and the stiffness of the geosynthetic material increase.

Ashour et al. (2022) performed laboratory tests to study the behavior of granular columns in soft clay under cyclic loading. The crushed basalt was used to form the granular columns. Tests were conducted under static loading and cyclic loading conditions by varying cyclic stress ratios and frequencies. The cyclic loading amplitudes were determined based on cyclic stress ratios (CSR), which is the ratio of cyclic deviatoric stress to static deviatoric stress at failure. CSR values of 0.6, 0.7, and

0.8 were used to represent dynamic stresses of 50, 60, and 70 kPa, respectively, which typically relate to bearing pressures in railway subgrades. It was found that unreinforced soil showed larger strains at lower frequencies, whereas reinforced soil exhibited stable behavior across the frequencies from 0.5 Hz to 3 Hz.

Shahu et al. (2023) studied the cyclic and monotonic behavior of floating and end-bearing columns installed in very soft clay beds to improve transportation infrastructure. Scaled laboratory experiments were conducted to simulate highway and railway traffic conditions. The study reported that cyclic loading-induced settlement were 4-11 times greater than monotonic loading under the same stress level. Granular columns improved ground exhibited stable deformation behavior within the first 100 cycles of loading under the stress amplitude of 7.5 to 18.7 kPa.

Xu et al. (2024) investigated the performance of pile-supported low embankments under cyclic traffic loading. The height of the model test embankment represented a typical 2m high low embankment in the field. Cyclic traffic loading was applied in three stages with amplitude of 10 kPa, 20 kPa, and 40 kPa, with each stage consisting of 10,000 cycles applied at 1 Hz frequency. Geosynthetic reinforcement of the columns reduced the cumulative settlement by 24.5 % and improved the loading capacity of the embankment.

2.4.4 Numerical analysis

Han and Gabr (2002) studied the behavior of geosynthetic reinforced pile-supported embankment over soft soil using numerical modeling. The study focused on the effects of embankment height, tensile stiffness of the geosynthetic material, and elastic modulus of the pile material on the stress concentration, soil arching, and tension in the geosynthetic material. The numerical modeling was conducted using the FLAC (Fast

Lagrangian Analysis of Continua) program. The foundation soil and the embankment fill material were modeled using a non-linear hyperbolic elastic model. Piles and geosynthetic material were modeled using linear elastic material properties. A drained condition was selected and effective stress parameters were used for cohesion and friction angle for soils and fill material. It was observed that the stress induced in the piles increased with the embankment height, geosynthetic stiffness, and modulus of the pile material. The soil arching ratio decreased with the height of the embankment and pile modulus and decreased with geosynthetic stiffness.

Murugesan and Rajagopal (2006) investigated the performance of geosynthetic encased granular columns by performing parametric analysis using the finite element program GEOFEM. A cylindrical unit cell was used to represent the granular column and the surrounding soil, with axisymmetric modeling due to the radial symmetry of the soil around the vertical column axis. The granular column and the soil were modeled using a non-linear elastic model, while the geosynthetic material was modeled as a linear elastic material. It was observed that the encasement of the top portion of the column up to a depth of 2 times of diameter is sufficient for substantial performance improvement. Smaller diameter columns performed better due to higher confining stresses in the encased column.

Ambily and Gandhi (2007) examined the behavior of granular columns in soft clay through experimental and numerical modeling using finite element analysis. Using PLAXIS software, FEM analysis was performed with 15 noded triangular elements, and Mohr-Coulomb's elastoplastic criteria was used to model the behavior of soft clay, granular columns, and sand. The results obtained from numerical modeling were compared with the experimental findings, showing good agreement in terms of ultimate load, load-deformation relationship, and failure modes. Results showed that single columns failed by bulging, with maximum deformation observed at a depth of 0.5 times the column diameter. Based on the results obtained, design charts and procedures were developed to ensure adequate safety and settlement control during the application of granular columns in the field.

Hanna et al. (2013) investigated the failure modes of single and group columns installed in single and group of granular columns installed in soft soil under a raft foundation. The numerical model was based on non-linear elastoplastic finite element analysis performed using PLAXIS V8 finite element software. Fourth order 15 nodes triangular elements were used to achieve accuracy in stress-strain distribution. A medium mesh was used globally, with refined meshes in areas of high stresses and displacement. The Mohr-Coloumb constitutive law was used to represent the behavior of granular columns and soft soil.

Hasan and Samadhiya (2017) studied the performance of geosynthetic reinforced granular piles in very soft clay by performing laboratory model tests and numerical modeling. The numerical modeling done in the study used PLAXIS 3D finite element software. The Mohr-Coloumb failure criteria were adopted for soft clay and stone aggregates used in linear elastic perfectly plastic behavior. It was reported that combined vertical and horizontal reinforcement provided the highest load intensity ratio (7.92-11.38 experimentally, 7.88-11.09 numerically).

Al Ammari and Clarke (2018) studied the effect of vibro-stone column installation on the performance of soft soil using PLAXIS 2D and 3D for numerical modeling. A single column was modeled as a displacement column to simulate the installation process of the granular column in the field. The settlement predictions obtained from the numerical study were compared with the field test results to validate the model. The study concluded that the vibro-stone column foundations should be modeled as a composite system rather than an independent unit to achieve more accurate prediction settlement and better design outcomes.

Miranda et al. (2021) analyzed the critical length of the granular column and the length of encasement using parametric numerical simulations. The study found that the critical length of encased columns ranged from 1.3 to 2.5 times the footing diameter, while for ordinary columns, it was 1.1 to 1.9 times the footing diameter. The critical encasement length was slightly shorter than the critical column length, typically ranging from 1.1 to 1.7 times the footing diameter.

Zhang et al. (2023) studied the behavior of floating geosynthetic encased granular columns supported embankments with basal reinforcement using a 3D hydro-mechanical coupled finite element model. It was observed that weaker substratum soils, such as very soil clay, resulted in higher pore water pressure and higher embankment settlement. The higher basal reinforcement stiffness decreases the tensile strain in the reinforcement, particularly at the embankment shoulder prone to lateral spreading.

Lang et al. (2023) presented a study on the dynamic behavior of piled embankments under train loading using a three-dimensional numerical model. The model incorporates a simplified kinematic hardening constitutive approach to simulate the behavior of soft clay under cyclic loading. It was observed that higher train speeds increase the cumulative settlement and slightly weaken soil arching. Train loading induced cumulative settlement was observed to increase with the number of load cycles and the embankment height. The settlement trend attains stability after an initial rapid increase.

2.4.5 Recycled waste materials

Studies have been reported on the use of construction and demolition waste, glass beads, and tire chips as replacements for conventional aggregates. Still, very few studies have been conducted on the use of recycled plastic granules. Also, the environmental impact assessment and cost estimation of the recycled materials are needed to better understand its field applications. This section explores a comprehensive literature review of recycled waste material's responses to traditional construction materials under static and dynamic loads.

Arulrajah et al. (2017) investigated the use of recycled plastic granules and demolition wastes as road construction materials. The plastic granules used in the study were derived from low-density polyethylene (LDPE), high-density polyethylene (HDPE), and linear low-density polyethylene filled with calcium carbonate (LDCAL). The study evaluated the stiffness, strength, and resilient moduli of material blends containing 3% and 5% plastic granules mixed with demolition wastes. LDCAL blends exhibited higher bearing capacity compared to HDPE and LDPE blends. However, adding plastic granules reduces the bearing capacity due to smoother particle surfaces.

Bostanci et al. (2018) explored the use of recycled aggregate and supplementary cementitious materials to produce low-carbon and cost-effective concrete. The study evaluates the environmental impact (CO_2 emissions), cost analysis, and performance of concrete mixes made with natural and recycled aggregates. Recycled aggregate mixes showed CO_2 emissions comparable to natural aggregate mixes, with a slight increase due to the processing of the recycled aggregates.

Belmokaddem et al. (2020) investigated the use of plastic waste aggregates composed of polypropylene (PP), high-density polyethylene (HDPE), and polyvinyl chloride (PVC) as a partial replacement for natural aggregates in concrete to address environmental challenges and promote sustainable construction practices. It was found that the use of plastic aggregates reduces the density of concrete, with PP achieving a reduction of up to 46%, making it suitable for application in lightweight concrete. Using plastic waste in concrete reduces the need for incineration, which releases significant amounts of carbon dioxide and other toxic compounds into the atmosphere. The incineration of PP and PE emits 812 kg eq C/t and 813 kg eq C/t, respectively. Recycling plastic waste into construction materials reduces the energy required and the emissions associated with mining and quarrying activities.

Alqahtani et al. (2021) studied the life cycle cost implications of using lightweight green concrete made with recycled plastic aggregates, specifically composed of linear low-density polyethylene (LLDPE) as a substitute for natural aggregates in concrete structures. The cost estimation was conducted using life cycle cost (LCC) analysis, which evaluates the total cost of an asset throughout its life cycle, including construction, maintenance, and end-of-life costs.

Kazmi et al. (2022) investigated the shear strength behavior of kaolin clay reinforced with granular columns backfilled using natural sand, manufactured sand, and crushed waste glass. Large direct shear tests were performed to compare the performance of these materials in improving the geotechnical properties of weak soils. The results showed that columns composed of crushed waste glass provide the highest friction angle and superior shear strength under higher normal stresses. Crushed waste glass repurposes nonbiodegradable glass as a filler material, thus reducing the burden on landfills and promoting sustainable waste management. Crushed waste glass replaced the natural sand and manufactured aggregates in field application, hence conserving depleting reserves of sand and natural aggregates.

Ponmalar and Revathi (2022) reviewed the works on using recycled plastic waste as a substitute for natural aggregates, aiming to address the environmental challenges and resource shortages in the construction industry. Studies have shown that replacing natural aggregates with plastic waste in the range of 10-50% reduces compressive strength by 34 to 67% but improves ductility and chemical resistance. Optimized replacement of aggregates and admixtures can help in achieving desired mechanical properties. The use of recycled plastics in construction activities requires further research to address technical, economic, and environmental challenges. There is a need to optimize designs, standards, and guidelines for the application of recycled plastic materials for safer and sustainable development.

(Saha et al. 2023) presented a study on the economic viability of recycling waste plastic as an aggregate in green, sustainable concrete (Fig. 2.15). The work addressed the major challenges of plastic waste mismanagement and unsustainable extraction of natural aggregates. The study focused on the economic, environmental, and social cost benefits of using recycled plastic aggregates as a replacement for natural fine and coarse aggregates in concrete. It was observed that the cost of concrete decreases with increased replacement percentages, with cost reductions ranging from 0.65% to 7.58% compared to conventional concrete. Plastic aggregate-based concrete showed acceptable mechanical properties, up to 30% replacement with increased tensile strength and workability.

Fig. 2.15 Flowchart depicting the process of fine and coarse plastic aggregates (Saha et al. 2023)).

(Saleem et al. 2023b) presented a study assessing the environmental impacts of producing recycled plastic pellets from polyolefin-based plastic waste using a life-cycle assessment (LCA) approach. Plastic waste was collected, separated, shredded, dissolved in xylene, and extruded into pellets. The environmental impact assessment was done focusing on categories like climate change, human toxicity, acidification, and fossil fuel depletion. It was found that recycling plastic waste reduces carbon emissions by 22.6% compared to virgin plastic pellets and 41.8% when solar-based electricity is used. Other impacts, such as terrestrial acidification and forest depletion, are reduced by 11 to 40% with 100% xylene recovery. The cost of producing recycled pellets is competitive with virgin materials making it economically viable for mass production.

(Jalili and Shafiee 2024) investigated the use of recycled ceramic beads to enhance the mechanical properties of low-plastic clays, offering an eco-friendly solution to reuse waste materials (Fig. 2.16). The work focussed on the monotonic, cyclic, and post-cyclic behavior of ceramic bead-clay mixtures under triaxial loadings. Ceramic beads of varying sizes (4, 6, and 9 mm) were mixed with clay in different proportions of 40%, 60%, and 80% to evaluate their impact on the mechanical properties of the composite soil mass.

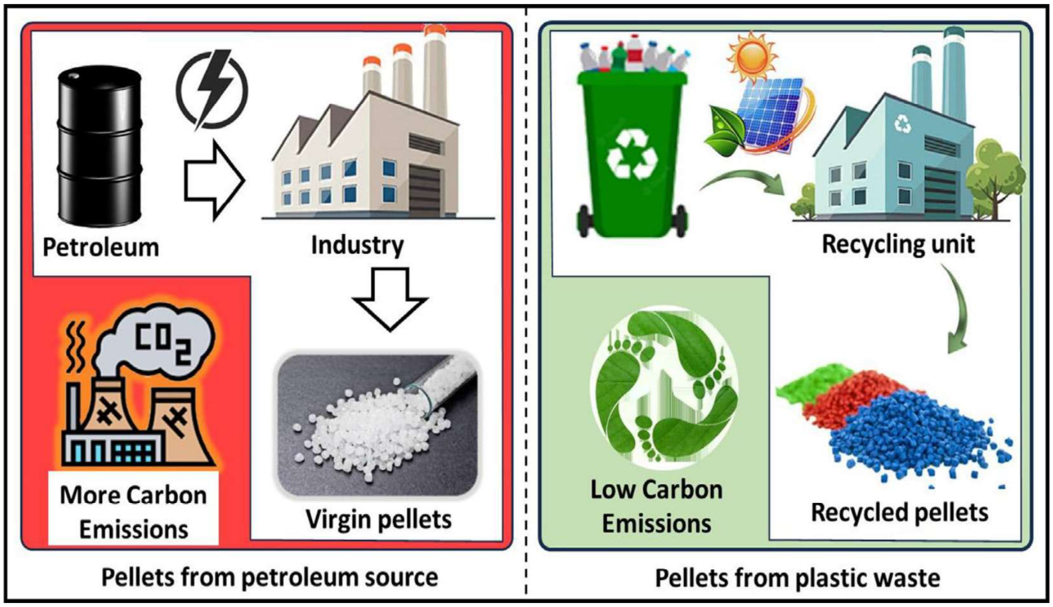


Fig. 2.16 Reduction of carbon emissions by recycling plastic wastes (Jalili and Shafiee 2024)).

It was observed that the effective friction angle, undrained shear strength, shear modulus, and damping ratio increase with the bead content, while normalized shear modulus decreases. The mixture with 60% bead content exhibited the highest post-cyclic strength, irrespective of bead size. It was reported that the mixtures can be used in embankment dam cores and waste disposal liners, reducing ceramic waste and improving soil properties.

2.5 Research Gap

The use of granular columns has significantly gained acceptance in the construction industry as a preferred ground improvement method for strengthening soft soil deposits.

The literature survey was conducted in the context of the research objectives and has helped to identify the following research gaps:

1. The use of waste materials in granular columns has not been done significantly. This needs to be studied in the context of sustainable infrastructure development.
2. Limited study has been done to observe the static as well as cyclic behavior of granular columns in soft soil foundations.
3. The current studies available on cyclic behavior consider only single-stage uniform amplitude cyclic loading variation; multi-stage cyclic loading of granular column foundations needs to be explored.
4. No literature is available on the application of recycled plastic material being used as an alternative filler material to conventional aggregates in granular columns.