

CHAPTER 1

INTRODUCTION

1.1 General

Ground improvement methods have gained popularity in recent years mainly due to the scarcity of suitable land for development and the need for large infrastructure projects in previously unsuitable locations. A significant amount of time and money could be saved if these projects were built on naturally available suitable sites. However, naturally occurring soil deposits usually don't meet the criteria for bearing capacity and serviceability requirements. In rapidly advancing economies like India, the demand for large-scale infrastructure projects such as high-speed railway tracks, expressways, airport runways, hydraulic structures like bridge abutments and piers, port areas with container yards, and large-scale industrial facilities is paramount for the country's rapid economic development. The subgrades of these major projects are subjected to high-intensity cyclic stresses caused by sinusoidal wave loads, traffic loads, earthquakes, and more during the construction and operation period (Wang et al. 2018).

The availability of major soil types in India is presented in Fig. 1.1. Soft soils are widespread in many parts of India, especially near coastlines, alluvial plains, river deltas, and river basins. These soils are undesirable for infrastructure development due to their low bearing capacity, excessive settlements, high compressibility, and low shear strength (McKelvey et al. 2004; Bo et al. 2005; Shivashankar et al. 2010). When subgrades consist of high silt and considerable sand content, they are highly susceptible to liquefaction phenomena due to cyclic stresses (Puri et al. 1996; Andrews and Martin 2000; Polito et al. 2008). The classification of soft soils based on

shear strength, as per (IRC: 113-2013), is presented in Table 1.1. In the past, when abundant land was available for construction activities, geotechnical engineers did not consider these sites for construction. However, due to urbanization and industrialization, many construction activities are now taking place on these sites, posing significant problems and challenges to geotechnical engineers.



Fig. 1.1 Availability of major soil types in India (Courtesy: www.Indiamaps.com).

Recently, the government of India approved seven railway projects, estimated to cost 32,500 crores. Additionally, the government has allocated approximately 2.8 lakh crores towards developing the road transport network. Significant financial resources are also being allocated to upgrade existing roads as part of the National Highway Development Programme (NHDP), alongside a focus on constructing new roads under the Pradhan Mantri Gram Sadak Yojna (PMGSY). However, the execution and

construction of these proposed high-speed rail and road network projects face many engineering challenges despite their potential benefits. The key challenge is the limited availability of appropriate sub-grade soil strata. Various ground improvement techniques are available to mitigate these issues and improve soft soil conditions. The selection of ground improvement techniques must meet several criteria, including site characteristics, type of infrastructural project, and financial considerations. The following are the ground improvement techniques used for soft soil improvement (Sivakumar et al. 2004).

1. Piles are primarily designed to transfer loads from structures to deeper, more stable soil layers or bedrock. They provide vertical load-bearing capacity but do not significantly improve the properties of the surrounding soil. They do not inherently improve drainage or reduce excess pore water pressure in soft soils. Pile installation can be more complex and expensive.
2. Preloading methods are mainly suitable for speeding up consolidation, but the slow increment rate of load-bearing capacity is unsuitable for time-bound large infrastructure projects.
3. Chemical stabilization entails combining lime, cement, or other chemicals into soft soil, which is not environmentally friendly and may sometimes result in adverse environmental concerns.
4. Soil reinforcement by granular piles (usually known as stone columns or granular columns) is a very effective ground improvement solution for problematic soft soils, speeding up consolidation, reducing differential settlements, and increasing load-bearing capacity.

Each ground improvement method possesses its unique set of merits and demerits. Among several ground improvement techniques, soil reinforcement with granular

piles is the better-suggested solution regarding reliability and financial feasibility (Meyerhof 1963; Hugher and Withers 1974; Barksdale and Bachus 1983; Castro et al. 2013).

Table 1.1 Classification of soft soils based on shear strength (IRC: 113-2013).

Consistency	Undrained shear strength, S_u (kPa)	SPT Value	SCPT value (kPa) (As per correlation given by Akca 2003)
Hard	> 400	>30	>6000
Very stiff	200-400	15-30	3000-6000
Stiff	100-200	8-15	1600-3000
Medium	50-100	4-8	800-1600
Soft	25-50	2-4	400-800
Very soft	<25	0-2	0-400

1.2 Granular pile

A granular pile is a dense aggregate column of granular material embedded in weak soil strata. Formerly called a stone column, it initially utilized only stones for filling. Nowadays, the term "granular pile" or "granular column" emphasizes the variety of granular fill materials used. Granular piles consist of compacted gravel or crushed stone arranged as a column using a probe vibrator. They support the load from the surrounding soil and act as vertical drains to dissipate excess pore water pressure. This widely used ground improvement technique improves load-bearing capacity, decreases the compressibility of soft and loose fine-graded soils, accelerates consolidation, reduces liquefaction potential, and minimizes differential settlement (Meyerhof 1963; Hugher and Withers 1974; Geoffrey 1976; Barksdale and Bachus 1983; Randolph et al. 1994; Muir wood et al. 2001; Murugesan and Rajagopal 2007; Malarvizhi and Ilamparuthi 2007; Ambily and Gandhi 2007; Veiskarami et al. 2011; Castro et al. 2013).

Granular piles mainly stabilize soft soils, such as soft clays, silts, and silty sands with fines greater than 15% (Barksdale and Bachus 1983). Major applications of granular piles include road and rail embankments, airport runways, bridge barriers, offshore bridge abutments, storage tanks, and power plants. In most of these applications, such as embankments for high-speed railway tracks, expressways, and airport runways, granular piles are subjected to static stresses due to overburden and cyclic stresses due to sinusoidal wave loads, traffic loads, earthquakes, and so on during construction and operation (Wang et al. 2018). This method is believed to have originated in France during the 1830s and has found widespread adoption, particularly across Europe, since the 1950s. In India, the utilization of granular piles commenced in 1970 (Datye and Nagaraju 1975). The diameter of granular piles typically used in the field ranges from 0.6 m to 1.2 m, and the length depends on the depth to which the soil bed is improved and the type of granular pile installed (either end-bearing or floating). In India, granular piles up to lengths of 15-20 m have been used. Fig. 1.2 represents a schematic view of installing granular piles in the field.

The effectiveness of granular piles can vary based on in situ soil properties and project requirements. Granular piles are best suited for soils with undrained shear strength (S_u) ranging from 7 to 50 kPa (IS 15284 (part 1) 2003). Specifically, ordinary granular piles (OGP) are ideal for soft soils with undrained shear strength (S_u) between 15 and 50 kPa (Barksdale and Bachus 1983). Under these conditions, granular piles achieve their load-bearing capacity through the generation of lateral earth pressure exerted by the surrounding soft soil, effectively countering bulging or deformation (Greenwood 1970; Barksdale and Bachus 1983; IS 15284 (part 1) 2003). This mobilization of soil pressure enhances the stability and strength of granular piles, enabling them to bear significant loads.



Fig. 1.2 Schematic view of installing granular piles in the field (Courtesy: Keller).

Nevertheless, in highly soft soils ($S_u < 10$ kPa), the soil's lateral confinement needs to be improved, resulting in the granular piles failing to achieve the necessary load-bearing capability. OGP's are also unsuitable for extremely soft soil deposits with sensitivity greater than or equal to 4 (IS 15284 (part 1) 2003). Due to the low shear strength of the surrounding soil, there is insufficient lateral confinement. Additionally, granular material intrusion into the soft soil is highly likely because there is no distinct separation between the granular pile and the surrounding soft soil. As a result, the load-bearing capability of the granular pile foundation is reduced, as it largely depends on the frictional qualities of the granular pile material.

The geosynthetic encasement is recommended to prevent the intrusion of granular pile materials and enhance the interface strength between the granular pile material and the surrounding soil. Geosynthetic encased granular piles have gained greater acceptance than ordinary granular piles because the encasement substantially enhances load-bearing capacity, minimizes differential settlements, enhances pile stiffness by restricting the movement of granular pile material into the soft soil, and

ensures better stress distribution. Considering all these factors, granular piles with geosynthetic encasement have proven to be the most reliable and cost-effective solution.

(W Van Impe 1986) was the first to provide geosynthetic encasement to granular piles in a vertical configuration (VEGP). Following that, several researchers conducted laboratory model tests on granular piles with different vertical encasements (Gniel and Bouazza 2009; Murugesan and Rajagopal 2009; Ali et al. 2012; Yoo and Lee 2012; Ghazavi and Nazari Afshar 2013; Dash and Bora 2013; Hataf et al. 2020; Sadr and Hataf 2021; Sadr et al. 2022). (MADHAV M. R. 1982) was the first to provide encasement through horizontal layers. In later stages, very few researchers conducted laboratory model tests on granular piles provided with encasement in the form of horizontal discs or horizontal strips (Sharma et al. 2004; Ali et al. 2014; Hasan and Samadhiya 2017). Limited research has been conducted on reinforcing granular piles by combining vertical and horizontal encasement (Hasan and Samadhiya 2019; Bazzazian Bonab et al. 2020). This study considered three varieties of geosynthetic materials with different tensile strengths as encasements for granular piles. The three encasement materials are geotextile (GT), geo-grid (GG), and combi-grid (CG).

1.3 Necessity of replacement materials to aggregates

This study also discusses the replacement of traditional aggregates with suitable waste materials with adequate strength and deformation properties. Generally, granular piles are made with aggregates. However, high-quality aggregates are not always readily available. The depletion of naturally existing materials is accelerating due to their excessive extraction to meet the enormous demand for infrastructure projects. This excessive quarrying leads to deforestation and soil erosion, adversely

affecting the environment. Due to the scarcity of these natural materials, it is now necessary to discover suitable replacement materials. Recently, global focus has been on advocating waste materials as replacements for aggregates in civil engineering projects. This approach aims to achieve cost savings, alleviate pressure on high-quality aggregates, and contribute to environmental protection.

1.3.1 End-of-Life Tires (ELTs)

To mitigate this detrimental environmental condition, this study focuses on recycling end-of-life tires (ELTs) into tire chips and reusing them in granular piles to replace traditional aggregates in soft soil improvement, thereby achieving engineering and environmental goals. ELTs, often known as scrap tires, worn-out tires, or discarded tires, are no longer usable. Every year, approximately one billion ELTs are produced globally, accounting for more than 2% of total solid waste production, and this waste tire volume is increasing significantly (Dabic-Miletic et al. 2021). However, the recycling sector only recycles nearly 10% annually. According to the Material Recycling Association of India (MRAI 2021), 1.5 million tons of ELTs are produced in India each year, with only 0.45 million tons being recycled annually.

The accumulation of bulk volumes of ELTs has very adverse effects on the environment and health. The improper disposal of ELTs poses severe hazards to our environment. The compaction of ELTs in landfills poses significant challenges since they tend to resurface over time, impeding land rehabilitation. Accumulating scrap tires provides an optimal habitat for vermin and insects, potentially harming public health. The potential fire risk is also a greater concern because these tires are highly flammable, as shown in Figs. 1.3 and 1.4. Proper waste management methods are adopted to mitigate these effects.



Fig. 1.3 Stockpiling of waste tires (a) On land (b) On water (Courtesy: recyclenation.com).



Fig. 1.4 Fire hazard due to the disposal of discarded tires (Courtesy: ecomena.org).

ELT management is a global issue with detrimental environment effects, demanding more focus on tire recycling and subsequent utilization in sustainable infrastructure applications. Current uses for ELTs include tire-derived fuel (TDF) production, ground rubber applications (such as new rubber materials, playgrounds, and sports surfaces), and usage in civil engineering applications. Recycling and reusing ELTs are considered more desirable solutions due to the environmental degradation that arises from the production of tire-derived fuel (Neaz Sheikh et al. 2013). In recent years, much research has focused on investigating various possibilities for recycling and reusing ELTs in civil engineering projects.

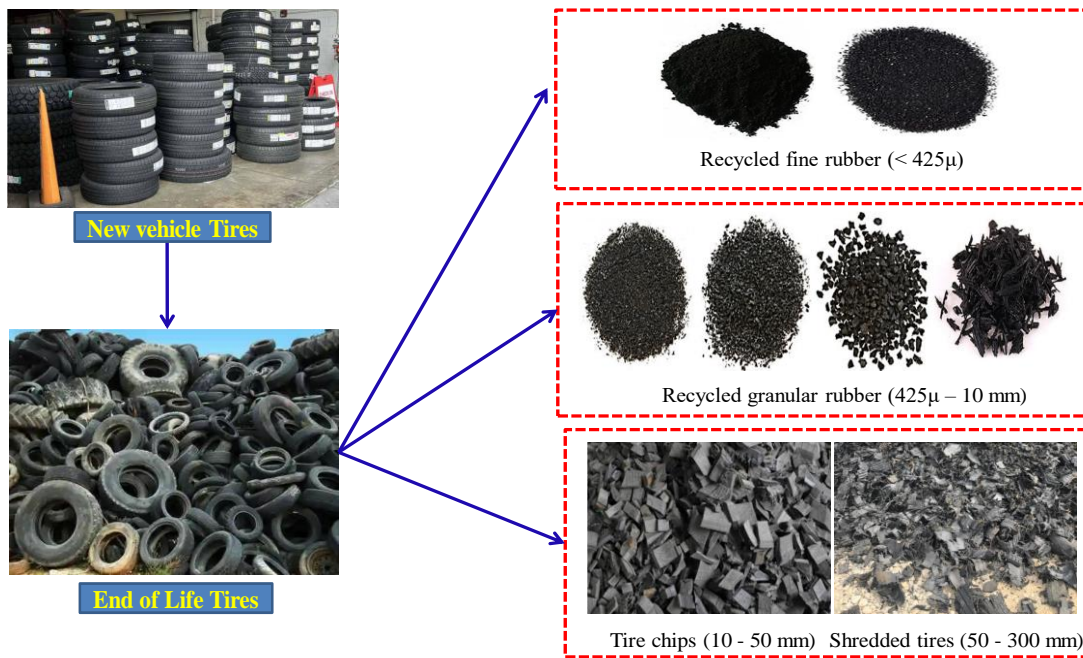


Fig. 1.5 Different recycled End-of-Life- Tire (ELT) products for civil engineering applications.

Managing ELTs, or waste tires, is a global issue that demands more focus on tire recycling and subsequent utilization in sustainable infrastructure applications. Recycling waste tire materials with good strength and deformation properties and reusing them in various civil engineering applications is challenging for geotechnical engineers. Recycled waste tire chips could replace conventional aggregates in various geotechnical applications. Partial or complete replacement of aggregates with tire chips as construction material in various ground improvement techniques can positively impact economic and environmental aspects. Recycled/shredded waste tire material has gained significant attention as a valuable construction material for improving soft soils due to its distinctive characteristics, including low unit weight, good strength, hydrophobicity, and high frictional properties (Lo Presti 2013; Humphrey 1999). The other applications of recycled tires as the use of tires to form tire bales and in the construction of earth ship houses. Tire bales represent another innovative use of recycled tires in civil engineering. These are formed by compressing

and binding whole tires into compact blocks. Tire bales have been applied in construction projects such as embankments, retaining walls, and slope stabilization. These bales not only provide structural support but also offer environmental advantages by diverting a large volume of tires from landfills. Given their properties, tire bales could be investigated further as an alternative material in ground improvement projects, offering additional drainage and load-bearing capacity, particularly in soft soil conditions. Another notable application of recycled tires is in the construction of Earth ship houses, a sustainable housing model that incorporates used tires as the primary building material. In these structures, tires are packed with soil to form sturdy walls that provide high thermal mass, helping to maintain consistent indoor temperatures. This method showcases the use of recycled tires not only as a structural component but also as a means of promoting sustainable building practices. The environmental and cost benefits of Earth ship houses further demonstrate the versatility of recycled tires in diverse construction applications. Fig. 1.5 illustrates the different recycled tire-derived products employed for various civil engineering applications.

1.4 Research objectives

This research aim is to assess the performance of ordinary and encased granular piles composed of optimum tire chips – aggregate mixture subjected to static and cyclic loading in soft soil improvement. So, this study's primary goal is to evaluate the optimum mix percentage of tire chips and aggregates for granular pile applications. This can be examined by carefully selecting suitable encasement materials and defining the appropriate confining stresses, loading frequency, and cyclic stresses for treated and untreated soft soils. Both static and cyclic loading conditions must be considered when granular piles are employed to improve soft sub-grades under large

infrastructure projects, as they are subjected to static overburden and cyclic stress induced by the repetitive loads imposed by vehicular traffic.

The analysis is carried out based on the "unit cell" concept. The unit cell typically includes the granular pile and adjacent or peripheral soil. The purpose of studying a unit cell is to understand how the granular pile interacts with the surrounding soil and how it influences factors such as settlement, bearing capacity, and overall ground improvement. Since granular piles are usually used in groups in the field to enhance soft ground, the group effect must be considered when analyzing an array of piles. The group action considers the interaction between adjacent piles, which depends on granular pile spacing. To accomplish the stated goals, the following specific objectives were outlined:

- i. To evaluate the shear parameters (c , ϕ , and ψ) of tire chips - aggregates mixture using large direct shear tests and select the optimum mix proportion.
- ii. To determine the optimum mix proportion of tire chips and aggregates in granular piles in soft soil under static and cyclic loading (both OGP and VEGP) and discuss different combi-grid configurations (VEGP, HEGP, and CEGP).
- iii. A parametric study will assess the behavior of granular piles composed of the optimum mix proportion under different cyclic characteristics (both OGP and VEGP).
- iv. To investigate the behavior of a group of granular piles with optimum tire chips- aggregates mixture under static and cyclic loading (12 granular piles in a group).
- v. To simulate laboratory static model tests using FEM validation using PLAXIS

3D.

1.5 Organization of the Thesis

The thesis is organized into eight chapters, as given below.

Chapter 1 introduced the research topic by briefly describing the different soft soil types, the improvement of soft soil bed by ordinary and geosynthetic encased granular piles, waste tire production, and management. It also outlines the research objectives, and the significance, and importance of this research work.

Chapter 2 reported the basic information about granular piles, including the working of granular piles, construction methods, failure mechanisms, and fundamental relationships of granular piles. This chapter also included reviews of the relevant literature under different categories: laboratory studies on granular piles under static and cyclic loading, numerical studies on granular piles under static loading, research on recycled waste tire materials in civil engineering, and concluding remarks.

Chapter 3 outlines the experimental methodology, including the test materials, sensors, setup for large direct shear tests, and the experimental procedures. It also outlines the setup and model test procedures for single and group granular piles subjected to static and cyclic loading.

Chapter 4 presents the interpretation and discussion of the results of the large direct shear tests. It explains the engineering properties of tire chip - aggregate mixtures, such as index properties and shear parameters. Finally, it discusses the selection of the optimum mix proportion of tire chip - aggregate mixtures in granular piles in terms of the improvement factor.

Chapter 5 presents the interpretation and discussion of the results of the laboratory model tests on a single granular pile subjected to static and cyclic loading, with and without combi-grid encasement in a soft soil bed. It determines the optimum mix proportion of tire chips-aggregates mixture and different combi-grid encasement configurations. The chapter also explains the behavior of a single granular pile under various principal parameters, including different encasement materials, cyclic loading amplitudes (q_{cy}), cyclic loading frequencies (f_{cy}), L/D ratios, granular pile end conditions, and surrounding soft soil conditions under cyclic loading.

Chapter 6 summarizes the interpretation and discussion of the results of the laboratory model tests on a group of granular piles under axisymmetric conditions subjected to static and cyclic loading, with and without combi-grid encasement, in a soft soil bed. The results are interpreted in terms of ultimate load intensity (q_{us}), dissipation of excess pore water pressure (p_{exc}), and pile-soil stress distribution (n), respectively.

Chapter 7 explains the numerical validation of model tests on granular piles under static loading, as presented in Chapters 5 and 6, using three-dimensional finite element analysis with Plaxis 3D software. It outlines the input parameters, focusing on the modelling considerations for the model test tank, granular piles, boundary conditions, soft soil bed, tire chips, aggregates, encasing materials, and various loading stages. The chapter concludes with a discussion and interpretation of the results derived from the model tests and the numerical analysis.

Chapter 8 summarizes the conclusions derived from this research work, discusses the limitations of the present study, and outlines the future scope of the work.

A list of references organized alphabetically at the end of the thesis.