CHAPTER 1

INTRODUCTION

1.1 General

Countries worldwide are striving to improve the standard of living for their citizens. The quest for urban infrastructure development is further aggravated in developing economies like India and other countries in the Indo-Pacific region. The ever-increasing population and large-scale migration of netizens towards urban centers for better economic and health services fuel this demand. The governments and policymakers in these places are constantly under pressure to provide state-of-the-art transport infrastructure to meet the industrial and residential needs of the local society.

The unique geography of India presents quite a contrasting distribution of its geographical terrain, with mountains in the north and a vast coastline extending over more than 7000 km in the southern part. The coastline along the southern peninsula and riverine delta areas along the country are underlain by soft clayey soil deposits. Soft soils are characterized by low undrained shear strength (< 25 kPa) (IRC:113 2013). The soft soils also exhibit high plasticity, and are susceptible to large settlement under traffic loading conditions (Sharma et al. 2004). The distribution of soft soils along the geography of India is shown in Fig. 1.1. The development of transport infrastructure like highways, expressways, airports, and urban housing infrastructures in areas having soft soils poses significant geotechnical challenges to the development of these projects.

The Government of India has undertaken several initiatives in the recent past to establish an exclusive high-speed rail network in the country to connect the primary business and industrial hubs. Also, the Bharatmala project under the Ministry of Road Transport and Highways (MoRTH) has planned the construction of nearly 50 national highway corridors, approximately 35,000 km long, connecting nearly 550 districts. The financial outlay of these projects is more than 80 billion USD (₹ 6.85 lakh crores). These projects are massive in scale, intricate in their implementation, and significant for national development. The alignment of these high-stakes infrastructure projects is often encountered with unsuitable or weak soil strata. Therefore, it is always a challenge for policymakers and engineers to mitigate the problems associated with implementing infrastructure projects in challenging soil strata and pave the way for the sustainable growth and development of the nation and humanity.

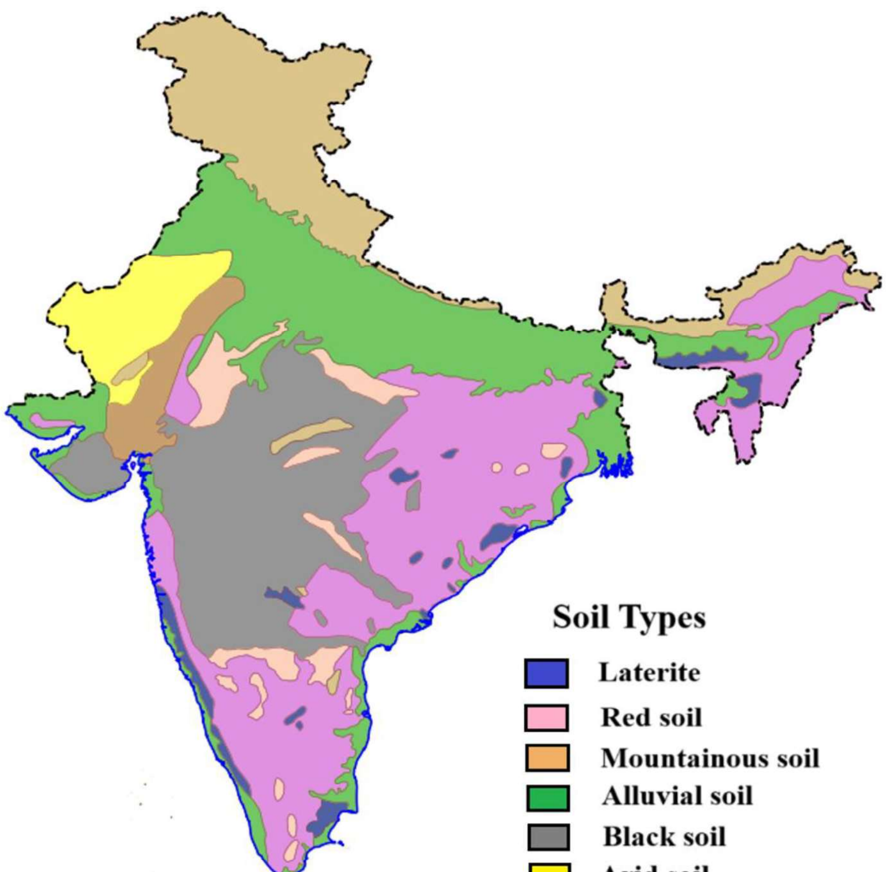

Fig. 1.1 Soil types found in India. (Source:https://geoportal.natmo.gov.in)

The problems associated with an unsuitable soil profile at the site can be dealt with by either abandoning the site altogether or modifying the in-situ soil to improve its engineering properties to meet the desired technical specifications of the soil. It is often most economically viable to go with the second option of ground improvement to meet the desired subgrade soil conditions for the infrastructure development. Several ground improvement methods have been established over the past to improve the problematic soils, making way for the construction of infrastructure on soft soil deposits.

1.2 Geotechnical characterization of soft soils

A typical classification of the soft soils found along the coastal plains of India is presented in Table 1.1. Also, based on the undrained shear strength and SPT value, the soils are classified from hard to very soft, as given in Table 1.2 (IRC:113 2013).

Table 1.1 Geotechnical properties of soft clays from different parts of India (IRC:113 2013).

Properties	Bombay	Outer Harbour Visakhapatnam	Kandla Port, Kandla	Willingdon Island, Cochin	Rann of Kutch
Depth of soft clay	1.0-20.0	12.0-18.0	12.0-20.0	21.0-28.0	3.0-17.0
Physical properties					
Liquid limit, w_l (%)	30-144	65-97	55-80	105-120	43-73
Plastic limit, w_p (%)	18-55	40-45	20-35	40-45	18-45
Natural water content, w (%)	40-139	80-90	35-75	65-102	40-80
Plasticity index, I_p	15-89	24-55	20-50	65-75	18-45
Specific gravity	2.32-2.88	2.65	2.72	2.53-2.60	2.61-2.78

Clay content	54-100	40-70	30-35	50-65	10-47
Engineering properties					
Undrained shear strength (kN/m^2)	15-45	20-40	17-35	5-15	5-20
Natural void ratio, e_o	1.96-2.81	2.47-2.57	1.1-1.5	2.18-2.30	1.5-2.0
Compression index	0.37-1.32	0.82-0.88	0.3-0.55	0.65-0.90	0.30-0.56
Coefficient of consolidation (cm^2/sec)	1.23 x 10^{-4}	1.06 x 10^{-4}	8.8 x 10^{-4}	2.54 x 10^{-4}	-
IS classification	CH-MH	CH-MH	CH-MH	CH-MH	CH-MH

Table 1.2 Classification of soft soils based on shear strength (IRC:113 2013).

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

1.3 Ground improvement methods

Various ground improvement methods are used to tackle the problems associated with unsuitable soils. Based on the type of soil and the nature of the problem associated, one or a combination of more than one of the following methods can be used (Hughes et al. 1975) :

- Densification or compaction: The method involves densifying loose cohesionless soil, using vibrating probes to compact the soil and enhance its stiffness. This method also helps mitigate liquefaction and excessive settlement in saturated silts and sands.
- Injection and grouting (compaction, permeation, or jet grouting): These methods can underpin existing structures and stabilize loose granular soils and subsurface voids.
- Preloading and dewatering (with or without PVDs, electrokinetic dewatering): These methods are used to speed up the consolidation process, thus helping reduce the overall time required for crucial projects, and their timely completion is of prime importance. These methods are mostly suitable in clayey soils.
- Chemical stabilization: This ground improvement method involves mixing chemicals like lime, cement, and fly ash with the soil to form a composite with improved stiffness and strength. Deep soil mixing is also one of its types, where in-situ soil is mixed with chemically treated soil and a binding additive to strengthen soil up to a depth of 30 metres (Gupta et al. 2025).
- Granular columns: This method involves the construction of load-bearing columns composed of stone aggregates or granular material using vibro-compaction to reinforce soft soils.

The ground improvement methods listed above have their specific utility and limitations. The application of a particular method depends not only on the soil type but also on the ease of availability of the raw materials, cost of implementation, and availability of human resources.

The use of granular columns has been done extensively over the years as a ground improvement method to strengthen soft clay deposits against settlements and as a vertical drain to improve drainage characteristics of clayey soils (Almeida et al. 2000; Murugesan and Rajagopal 2006; Roa et al. 1992). Several applications of granular columns have been reported by studies done over the years:

- Bearing capacity improvement of soft soils for the development of transportation routes like expressways and highways.
- Reduction in settlement of embankments constructed over soft soil beds.
- Improvement in drainage behavior of cohesive soils.
- Reduction in liquefaction potential of loose silty and sandy soils.
- Improving the rate of consolidation of cohesive soils thus reducing the time of completion of critical projects.

1.4 Granular column

Granular columns, commonly known as stone columns, have been effectively used to improve soft soils over the last fifty years(Barksdale and Bachus 1983; Greenwood D A 1970). Conventionally, granular columns are constructed as cylindrical inclusions of compacted granular material in natural ground. The granular column is constructed by compacting loose granular aggregates into the soil with the help of a vibratory probe. The schematic process of granular column installation is presented in Fig. 1.2. These columns are typically 0.6 m to 1.2 m in diameter. Also, based on the depth of the soil bed to be improved, the length of the column may extend up to 15-20 m. The granular column may be constructed in a floating or end-bearing configuration. The bottom of an end-bearing column rests on a hard stratum. The granular column imparts additional load-carrying capability to the native soil by improving its stiffness. Thus, the higher stiffness granular column-soil mass composite bears the extra portion of the load coming onto the soil.

The design and construction of granular columns have mainly evolved with the use of mechanized and advanced machinery, resulting in their application as an alternative to conventional foundation systems such as piles (McCabe et al. 2009). Granular columns have been used to strengthen foundations in soft to firm clays and loose silty soils (Barksdale and Bachus 1983). Granular columns are ideally suited for cohesive soils having an undrained shear strength of 7-50 kPa (IS: 15284 (Part 1) 2003). It has been reported in previous studies that when axial load acts on granular columns, they bulge laterally in the top portion below the surface, thus deriving additional lateral confining pressure from the surrounding soil (Black et al. 2007; Bouassida et al. 1995b).

1.4.1 Encased granular column

The working of granular columns is explained in the previous section. It has been reported that columns derive their load-bearing capacity from the lateral confining pressure of the surrounding soil (Guetif et al. 2007; Raithel M. et al. 2002). Granular columns installed in very soft soils (S_u<15 kPa) may not provide significant load-bearing capacity due to a lack of confining pressure from the surrounding soil (IS: 15284 (Part 1) 2003). The intrusion of soft soil into the column may reduce its stiffness, thus decreasing the loading capacity of the composite soil. The encasement of the column with a geosynthetic was proposed by Van Impe in 1985 for the improvement of soft soils (Van Impe and P. Silence. 1986). Several studies have been done over the years thereafter by using different geosynthetic encasements to enhance the settlement behavior and load-bearing capacity of granular columns by wrapping geosynthetic around the column along its length. The presence of geosynthetic encasement provides additional confinement to the column material. The encasement also prevents the intrusion of the aggregates into the soil, thus helping maintain column stiffness and its frictional property. Geosynthetic-encased granular columns have been preferred over ordinary granular columns due to their tensile stiffness and other advantages mentioned earlier (Hasan and Samadhiya 2017; Malarvizhi and Ilamparuthi 2007; Murugesan and Rajagopal 2010; Zhang et al. 2020). The use of stiffer geosynthetic materials like geogrid has been done to control the higher settlement response of foundations in soft soils (Das and Shin 1994; Gniel and Bouazza 2009). The present study used biaxial geogrid material as an encasement for the granular columns.

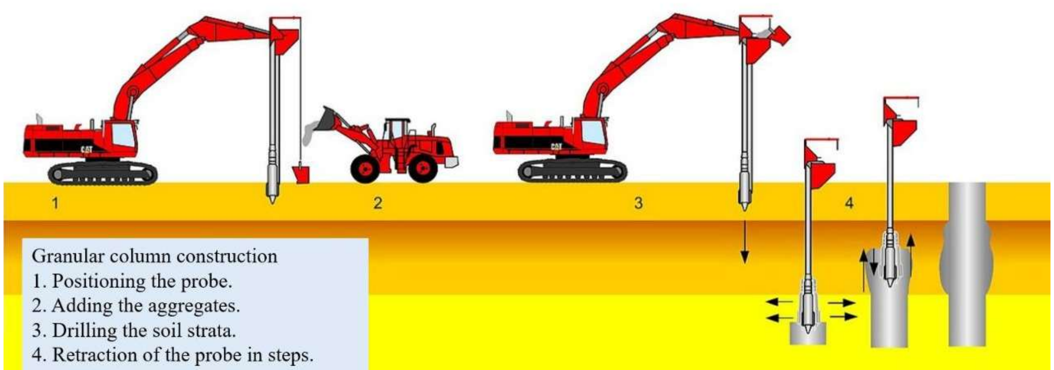

Fig. 1.2 Schematic process of granular column installation (Courtesy: Cofra B.V.).

1.5 Need for the present study

The use of granular columns as a ground improvement method has been well established through its various applications over the years. Also, the availability of exhaustive literature on the behavior of granular columns under static loading has led to a better understanding of its utility in field applications (Hanna et al. 2013; Hosseinpour et al. 2015). Many of the instances for the application of granular columns involve the improvement of soil for the development of transport infrastructure. These transportation routes are subjected to vehicular loads that are cyclic in nature. The studies done on the granular columns to analyze the cyclic load behavior of column-reinforced soil are still evolving (Aghili et al. 2021; Shahu et al. 2023; Yoo and Abbas 2019; Zhang et al. 2020). The effect of cyclic load on the stress distribution over the soil mass and the column has been found to be affected by the nature of column material and geosynthetic encasement (Gao et al. 2021; Muni Pradeep and Kumar 2024; Yoo and Abbas 2020).

Stone aggregates have been conventionally used as raw materials for the construction of granular columns. These aggregates are obtained from stone quarries, which are naturally occurring non-renewable resources. Also, the entire quarrying and transportation process of aggregates results in large-scale emissions of carbon into the environment. The unabated exploitation of these natural resources is not sustainable for human-led growth in the long run. An artificial scarcity of construction materials is highly possible in the near future. Therefore, there is a dire need to look for possible alternative materials. Few studies done in this area have shown the possibility of using waste materials like construction and demolition wastes, glass beads, and used plastics as alternative materials (Kazmi et al. 2022; Ponmalar and Revathi 2022; Premathilaka et al. 2024). The use of shredded rubber tire chips has been done as a replacement for aggregates in a few studies (Ayothiraman and Soumya 2015; Pradeep et al. 2023; Shariatmadari et al. 2018).

The annual plastic waste generation in India was approximately estimated by the Central Pollution Control Board (CPCB) to be 3.5 million metric tonnes in the year 2020 (CPCB 2020). The baseline report on waste plastic by the United Nations Environmental Programme (UNEP) shows that India is the fifth largest plastic waste generator globally (UNEP 2020). Plastic debris from land sources is found to contribute more than 80 % of plastic waste coming to the marine environment (Law et al. 2014; LI et al. 2016). Aquatic animals like fish, turtles, and other species are severely affected by marine contamination with microplastics, which are ingested by these organisms (Rochman et al. 2019; Steer et al. 2017). It has been reported by UNEP that only a part of the plastic waste generated globally (<20%) is recycled, and the rest is dumped in landfills or openly disposed of (Fig. 1.3). Very few studies have been done recently to assess the application of recycled plastic in construction activities (Belmokaddem et al. 2020; Ponmalar and Revathi 2022).

(a) (b)

Fig. 1.3 Plastic waste pollution a) over land (Courtesy: Getty Images); b) in the ocean (shutterstock.com).

The present study strives to use recycled plastic waste as an alternative to conventional aggregates by using plastic granules as filler material for granular columns. The recycling process of waste plastic into usable granular material is shown in Fig. 1.4. As a part of this study, granular columns (GC) made of stone aggregates and plastic granular columns (PGC) made of recycled plastic granules were used to reinforce the soft clay bed. Model tests were conducted in the laboratory on a single column bed and an embankment constructed over a group of columns to study their behavior under the action of static and multi-staged cyclic loading. The results of the tests are reported and discussed in the subsequent chapters.

Fig. 1.4 Recycling process of waste plastic to produce granules.

1.6 Research objective

The primary aim of this research work is to analyze the behavior of GC and PGC-reinforced soft clay beds subjected to static and multi-staged cyclic loading in soft soil ground improvement. The following objectives have been set to achieve the above-mentioned research goal:

- To study the effect of different parameters (Length-diameter ratio, undrained shear strength of soil, and geosynthetic encasement) on the single granular column (GC) and plastic granular column (PGC) reinforced soft soil bed under static loading.
- To study the effect of cyclic loading on soft soil bed reinforced with a single granular column and a plastic granular column.

- To study the vertical bearing capacity and deformation of a model embankment constructed on a clay bed reinforced by a group of granular columns (GCs) and plastic granular columns (PGCs) foundations under static and cyclic loading conditions.
- To study the failure modes of the granular column inclusions using a column exhumation technique after tests and compare them with the results obtained for different column configurations.
- To perform a three-dimensional, axisymmetric, finite element numerical simulation of tests on single columns and a group of columns to verify the model test results.

1.7 Organization of the thesis

The present study is compiled into seven chapters (sections) as mentioned below:

Chapter 1 The introduction of the research topic is presented in this chapter. A brief summary of the ground improvement method used in soft soils using granular columns is presented. The use of granular columns, geosynthetic encasement, and recycled plastic granules in ground improvement is also discussed. The objective and the need for the present study are outlined in this section.

Chapter 2 This chapter provides basic background information on granular columns, such as working, design, and construction, fundamental concepts, and failure mechanisms. A review of the literature on granular columns, which includes laboratory and numerical studies on single and groups of columns under static and cyclic loading, is presented. The research gaps available from this review help to justify the need for the present study.

Chapter 3 A detailed description of the materials used in the model tests, along with the method of sample preparation, testing equipment, and experimental procedures, is presented in this section. The model scaling considerations and the scheme of loading in all the model tests are given here.

Chapter 4 The results of the model tests on a single granular column (GC) constructed in a soft clay bed under the static and multi-staged cyclic loading conditions are presented in this section. The tests were conducted on ordinary and encased columns in floating and end-bearing configurations. The test results help determine the optimum length of the columns, the effect of geosynthetic encasement, and column material on the loading and deformation behavior of the reinforced soil.

Chapter 5 The behavior of an embankment supported on a group of floating and end-bearing granular columns in soft clay under traffic loading conditions is presented in this section. The failure pattern of the columns with or without geosynthetic encasement under static and multi-staged cyclic loading is observed. The results of the model tests are interpreted by calculating the load-bearing capacity, the excess pore water pressure development, and the stress concentration ratio of the column.

Chapter 6 A three-dimensional finite element numerical analysis of the model tests under static loading conditions is presented in this section. The results obtained from the laboratory model tests on a single column and a group of columns supporting an embankment are validated through numerical modeling using Plaxis 3D software. The parameters used in this are column configuration, mesh sensitivity, soil types, boundary conditions, and loading.

Chapter 7 A summary of the conclusions drawn from this study is presented in this section. This chapter also discusses the limitations and future recommendations for further study in this area.