# CHAPTER 1

# INTRODUCTION

## **1.1** General

India has about 6000 km long coastal lines, and deposits of soft clayey soil are present all along the coastal line and the nearby delta areas that cover a vast area of the Gulf of Kutch, the shores of the Gulf of Khambhat, etc. The natural moisture content of these soft soil deposits varies from 40 to 100%, and the in-situ shear strength generally ranges from 5 to 20 kPa (IRC:113 2013). These areas of soft ground impose geotechnical constraints that can cause disasters in ports, harbors, building foundations, road sub-base and subgrade, road embankments, and many other constructions due to their higher water content, high compressibility, and lower bearing capacity (Wu et al. 2021). The availability of soft subsoils along the coastal plains is shown in Fig. 1.1.

India's unique geological features and the prevalence of soft soils in numerous locations require careful planning and engineering considerations before any construction over the soft soil. The Government of India (GOI) has initiated extensive plans to establish bullet trains, or high-speed rail (HSR) routes, that connect important cities and regions. Furthermore, GOI has initiated Bharatmala Pariyojana as one of the most extensive road infrastructure development programs, aiming to construct and upgrade about 34,800 km of National Highway. The project includes the development of economic corridors, inter-corridors, feeder routes, coastal and port connectivity roads, and border roads to improve connectivity and facilitate freight movement. Therefore, there is a requirement for construction over soft soil to satisfy the demand for rapid construction of railways, highways, and expressways in India.

**Fig. 1.1** Soft soil along coastal plains in India (IRC:113 2013).

Improving the engineering properties of highly compressible soil or replacing the soil with better-quality soil are the two options available to get over construction challenges on such poor-quality ground. Several ground improvement techniques have been established to reduce the difficulties associated with the construction on soft ground and to provide reinforcement to such soft soil deposits.

## **1.2** Geotechnical characterization of soft soils

Typical geotechnical properties of soft soils along the coastal plains are summarized in Table 1.1 (IRC:113 2013). Based on the unconfined compressive strength and SPT value, the soil is classified as ranging from soft to hard. Table 1.2 presents the classification of soft soils on the basis of shear strength, standard penetration test (SPT) value, and standard cone penetration test (SCPT) value, showing a broader correlation between them.

**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) | $1.23 \times 10^{-4}$ | $1.06 \times 10^{-4}$ | $8.8 \times 10^{-4}$ | $2.54 \times 10^{-4}$ | - |
| 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 (kPa) | SPT value (N) | 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 |

## **1.3** Ground improvement techniques

To reduce the settlement and increase the ultimate bearing capacity of the soft soils, very limited ground improvement techniques are available. For different types of soil and types of improvement required, the widely used ground improvement techniques are:

- Replacement: complete soil replacement (Stone column, piling),
- In situ deep compaction (vibro-compaction, compaction piles, dynamic consolidation),
- Injection and grouting (electro-kinetic injection, chemical, pressure, or jet grouting),
- Precompression (preloading with and without drains, electro-osmosis),
- Thermal stabilization (heating and freezing),
- Chemical stabilization (deep soil mixing).

There are benefits and drawbacks associated with each of these ground improvement methods. Soil replacement has not shown to be a practical approach in recent years. Due to environmental limitations, the massive amounts of soft soil that have been excavated became problematic to dispose of. Furthermore, high-quality fill material is frequently unavailable at a reasonable cost. Large amounts of stones are required for the formation of stone columns, and these stones may or may not be present at the location. Both sandy and clayey soils can benefit from the densification approach; nevertheless, it causes a lot of noise and vibrations and may have an impact on neighboring structures. A pile foundation is recommended where its settlement is restricted to significantly less value and used for rigid and heavy structures as it is very costly. The long-term process of consolidation techniques may have negative effects on nearby buildings as a result of consolidation settlement. The thermal stabilization approach works best in short-term scenarios.

Among all the ground improvement techniques, deep soil mixing is a promising technique that can be used for all types of soils, like loose sandy soils, reclaimed soils, peats, soft clays, and mixed soils (Bruce 2001; Porbaha et al. 2000).

## **1.4** Deep soil mixing

Deep soil mixing is an in situ soil treatment technology whereby the soil is blended with cementitious or other materials using a mixing auger to a large depth (Kitazume & Terashi 2013). These materials are generally referred to as "binders" and can be introduced in dry or slurry form. Ordinary Portland cement (OPC) is a typical civil engineering construction material mainly used as a binder in the DSM method. Portland cement or lime, or a mix of cement and lime, is usually used as a binder in ground improvement projects on soft soil foundations (Terashi 2003).

Since the Port and Harbour Research Institute (PHRI) in Japan and the Swedish Geotechnical Institute in Sweden introduced the deep soil mixing technique around fifty years ago, it has been widely used for improving soft soil ground. Port and Harbour Research Institute (PHRI) of the Japanese Ministry of Transport initiated the research on the deep mixing method and the concept of lime stabilization of marine clays published in the literature in 1968 (Yanase 1968). (Okumura and Terashi 1975; Terashi 1997) performed laboratory tests on different types of clays to investigate the engineering properties of clay stabilized with lime and cement and found that unconfined compressive strength of the order of 100 kN/m$^2$ to 1 MN/m$^2$ is easily gained in cement-stabilized soils. Since then, it has been used in other parts of the world.

Due to its speed and affordability, DSM technology has been used to stabilize soft to extremely soft clays for the construction of various infrastructure projects around the globe. The major applications of DSM have been to reduce settlements under embankments, support light buildings and bridges, improve slope stability, protect structures surrounding the excavation site as a foundation of structures, control seepage and cut-off barrier, mitigation of liquefaction potential, increase drivability for tunneling in soft ground, ground anchorage/soil nailing, and vibration impediment (Andromalos and Bahner 2003; Bruce and Turner-Fairbank 2000; Porbaha et al. 1998). For structures such as road embankments subjected to low to medium loads, the DSM technique is more practical and economical than more expensive methods, such as piling (Bouazza et al. 2004).

Several features of deep soil mixing include a wide range of applications by rapid solidification of soil that reduces construction time, and required strength can be achieved by using an adequate percentage of binder and causing low environmental impact during construction. DSM is a technique that has also been employed for in situ stabilization of contaminated ground and groundwater at hazardous waste sites by eliminating excavation and in situ fixation of contaminated ground that might endanger surrounding structures (Yanase 1968).

Numerous factors are known to affect stabilized ground's bearing capacity and failure pattern, such as type of soil, different types of binders, amount of binder content, type of column, i.e., end bearing and floating, area replacement ratios, depth improvement ratio, and stress concentration ratio (Bouassida et al. 1995; Chai et al. 2002; Dehghanbanadaki et al. 2016; Rashid et al. 2015, 2018; Said et al. 2019; Yin and Fang 2010).

### 1.4.1 Working Principle

The process of the DSM technique consists of the following steps:

1. A specialized drilling rig with a rotating mixing blade and auger at the bottom is set up at the required place.
2. The drilling rig is penetrated up to the required depth.
3. As the mixing wings rotate and penetrate at the required depth of treatment, the binder (cement slurry, lime, or other stabilizing material) in powder or slurry form is discharged from the bottom of the mixing head.
4. The binder is mixed with the soil through the mixing blades of the drilling rig as the drill moves up and down. This process is repeated along the vertical length until the entire volume of soil is mixed with binder. A stabilized column of the improved soil is formed through this mixing of soil and binder.
5. Multiple columns are installed in different patterns depending on the required design to form the stabilized foundation.

6. Due to the chemical reaction between the soil and the binder, the soil later hardens and gains strength after the curing time, which varies from a few days to several weeks, depending upon the soil and binder used.
7. The strengthened soil is checked to make sure it satisfies the required specifications once it has cured.
8. Once the required strength is reached, the site is prepared for the construction of structures. The general working procedure in the DSM technique is shown in Fig. 1.2.

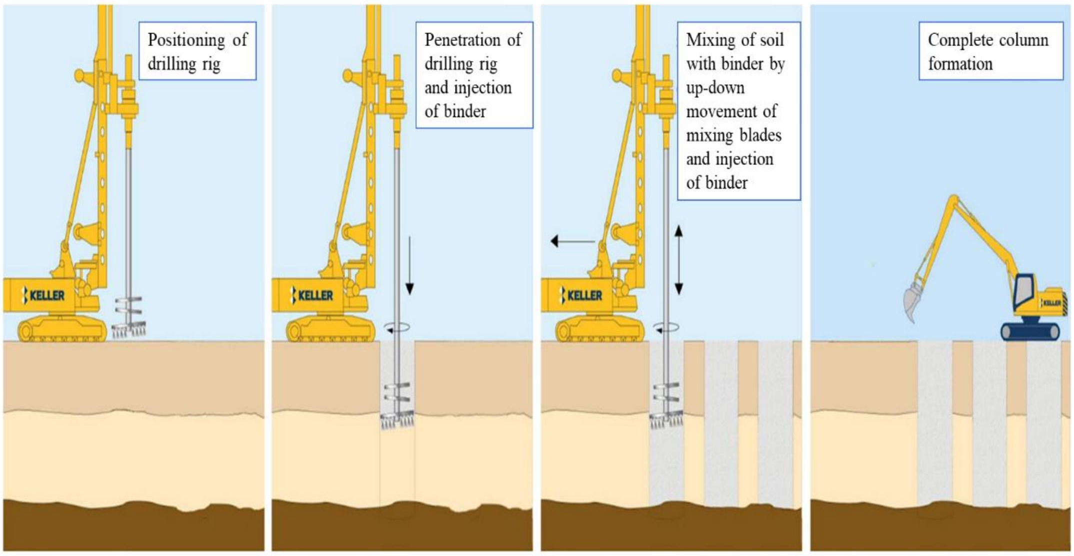

**Fig. 1.2** Column installation process of DSM technique (Courtesy: Keller).

### 1.4.2 Design Steps of Deep Soil Mix Columns

In general, the design of deep soil mix treatment involves the following steps:

1. Select the binder and optimum dosage levels of the binder following the laboratory mix design and analysis.

2. Select the water-binder ratio at which the maximum performance of DSM columns can be achieved.

3. Determine the geometric parameters, i.e., length, diameter, and spacing of the DSM columns based on the properties of the treated and untreated soil and results obtained from laboratory testing, configuration (block, panel, group, and grid) of columns, area improvement ratio ($A_r$) and installation pattern (triangular or square).

## **1.5** Geopolymer as a sustainable binder

Cement stabilization provides a substantial increase in strength in a short time frame due to cement hydration, ion exchange reaction, and the formation of pozzolanic reaction products (Horpibulsuk et al. 2011; Kang et al. 2017; Miura et al. 2001). However, OPC manufacturing exhausts a huge amount of natural resources and energy, and the process releases about 8–10% of the anthropogenic $CO_2$ per year into the atmosphere, causing greenhouse gases (Davidovits 1991, 2011; Oates 1998). About 1 ton of $CO_2$ is released during the manufacturing of 1 ton of OPC (Garcia-Lodeiro et al. 2014; Sargent et al. 2016; Zhang et al. 2013). Developing more sustainable binders that can replace these traditional binders is necessary.

In recent years, research has been conducted to utilize the industrial by-products in the DSM technique without compromising the soil stabilization capabilities. Either industrial wastes like blast furnace slag, steel slag, fly ash, etc., can be admixed in some percentage with cement, which will reduce the cement content in DSM, or cement can be wholly replaced with some green cementing material, i.e., geopolymer that will have the same engineering properties as cement. Research has been conducted to investigate the admixing of various industrial by-products with cement, and the increase in strength and stiffness was found to be enhanced (Bushra and Robinson 2013; He et al. 2020; Jongpradist et al. 2010; Yi et al. 2014a).

Another potential greener alternative is alkali-activated industrial by-products, also known as geopolymers, which have a lower environmental impact and even higher strength than cement (Davidovits 1991, 2008; Garcia-Lodeiro et al. 2014; Sargent et al. 2013; Yaghoubi et al. 2018; Yi et al. 2015). Geopolymer provides several benefits in addition to being environmentally friendly, including excellent strength and durability, rapid setting, heat resistance, low swelling and shrinkage, and reduced alkali-silica reaction. Geopolymerization is a technique in which a sodium/potassium-based alkali activator dissolves the amorphous alumina and silica in the precursors, yielding calcium aluminate hydrate (C-A-H), calcium silicate hydrate (C-S-H), calcium aluminate silicate hydrate (C-A-S-H) or sodium aluminate silicate hydrate (N-A-S-H) gel (Davidovits 2011). Industrial by-products like fly ash (Chen et al. 2023b; Hamid and Alnuaim 2023; Li et al. 2023b; Murmu and Patel 2020; Yaghoubi et al. 2022), blast furnace slag (An et al. 2022a; Luo and Zhang 2023; Sargent et al. 2016; Su et al. 2023), metakaolin (Zhou et al. 2021), rice husk ash (Zabihi et al. 2018), calcium carbide residue (An et al. 2022b; Li et al. 2021; Wu et al. 2024), palm oil fuel ash (Sukmak et al. 2019), glass powder (Ramezani et al. 2023), dolomite (Barbhuiya 2011), eggshells (Acharya et al. 2023; Anburuvel et al. 2023), silica fumes (Hossein et al. 2023) etc., can effectively synthesize as a precursor to produce geopolymer. Over the last few decades, extensive research has been carried out on the utilization of geopolymer in concrete, ceramic, shallow foundations, and the base of pavement, with less attention paid to soft soil stabilization.

In this thesis, thorough experimental work and model tests on GGBS and dolomite-based geopolymer for deep soil mixing technique treatment of soft soil ground are conducted to address the gaps described above.

## **1.6** Significance and importance

In recent years, deep soil mixing (DSM) has gotten into prominence as an effective ground improvement technique for the stabilization of soft to very soft soils subjected to low to medium loads (Bergado et al. 1996; Bruce 2001; Chai et al. 2010; Liu et al. 2022; Porbaha 1998). This technique involves mechanically mixing the binding materials or other additives with the in-situ soil to improve its engineering properties. Generally, ordinary Portland cement (OPC), lime, or a combination of both are used as a traditional binder in the DSM technique (Fang and Yin 2007; Horpibulsuk et al. 2005, 2011; Kang et al. 2017; Lee et al. 2005; Miura et al. 2001). There is a dire need to utilize waste materials as an alternate stabilizer to reduce the carbon footprint associated with traditional binders.

This study focuses on developing a combination of geopolymer materials that can fully replace the utilization of traditional binders to stabilize soft soil foundations in geotechnical engineering. GGBS and dolomite are used as novel precursors that can produce high calcium geopolymer. Granulated blast furnace slag is a by-product generated from the ferrous industry during the manufacturing of pig iron. When finely grounded, ground granulated blast furnace slag (GGBS) is formed that has moderate cementitious properties (Preetham and Nayak 2019). 300–540 kg of blast furnace slag is produced in the production of 1 tonne of pig or crude iron. According to the Indian Bureau of Mines (2020), India produces around 24 million tonnes of blast furnace slag annually. The World Steel Association (2019) states that blast furnace slag production was around 312–374 metric tonnes in 2018. Dolomite is an anhydrous carbonate material composed of calcium magnesium carbonate ($CaMg(CO_3)_2$). Dolomite rock that contains either calcite or a mix of calcite and magnesite is also called dolomitic limestone. It is obtained from natural sedimentary rocks worldwide and is generally used as a flux in the iron and steel industry (Ngamcharussrivichai et al. 2010). While crushing the dolomite stones, 20–40% of fine particles are produced, which are further disposed of as waste material. Using GGBS and dolomite in soil stabilization reduces construction costs and disposal issues of waste.

Partial replacement of GGBS with dolomite has shown stronger durability performance along with better resistance against sulfate attack, leaching, and carbonation compared to using only GGBS as a precursor (Machner et al. 2018). The addition of dolomite in alkali-activated S results in the formation of a hydrotalcite phase that intermixes with the calcium aluminosilicate hydrate (C-A-S-H) gel at a very fine scale, improving the durability and strength of the matrix (Ye et al. 2019, 2020). Compared to other waste materials like waste glass, metakaolin, fly ash, slag, red mud, potassium tailings, iron tailings, copper tailings, etc., dolomite's abundance and potential durability can make it a more reliable choice. Also, dolomite can provide additional benefits like lower carbon footprint and specific chemical resistance.

Therefore, there is a need to perform laboratory tests to assess the mechanical and microstructural properties of soft soil blended with GGBS-dolomite based geopolymer. The behavior of soft clay under static loading is quite complex, and the dynamic loading conditions make the scenario worse. Although there are several studies related to the static mechanical properties of geopolymer-stabilized soil (Ghadir and Ranjbar 2018; Phetchuay et al. 2016; Radovic and Puppala 2019), the studies on the understanding of cyclic loading amplitude, frequency, and confining pressure in analogy with the cyclic performance of geopolymer-stabilized soft clay are limited. The deformation behavior of soft clay under long-term loading cycles is significant as subgrade soil is subjected to long-term loading cycles at a stress level below its shear strength (Chazallon et al. 2006; Moses and Rao 2003). Therefore, it is vital to understand the cyclic behavior of geopolymer-stabilized soft clay, as in the construction of highways and railway embankments, the ground is subjected to repeated vehicle loading.

Furthermore, laboratory model tests need to be performed on a single-column foundation and embankment over a group-column foundation under static and cyclic loading similar to transportation routes to study the load settlement behavior, bearing capacity, and failure pattern of the geopolymer stabilized soil column (GPSC) improved ground. In addition, a life cycle assessment of geopolymer in comparison to OPC is necessary to show that geopolymer is a sustainable and eco-friendly construction material.

## **1.7** Research objective

The present research aims to assess the performance of geopolymer-stabilized soil columns (GPSCs) subjected to static and cyclic loading in soft soil ground improvement. To accomplish the stated goals, the following objectives were outlined:

- To evaluate the feasibility of using the geopolymerization technique for engineering improvement of soft kaolin clay using GGBS and dolomite as a precursor and Na-based liquid activator for the alkali activation process.
- Determination of the optimum mixing proportion of GGBS and dolomite by evaluating different engineering properties of the GGBS and dolomite-based geopolymer stabilized soft soil, such as shear strength, microstructure analysis, and leachability analysis for its utilization in the DSM technique and comparison with traditional binders.
- Investigate the undrained shearing behavior of geopolymer-stabilized clay using triaxial tests under static and dynamic loading conditions.

- To examine the behavior of a single geopolymer-stabilized soil column (GPSC) as a DSM column in soft soil ground treatment under static and cyclic loading.
- To study the vertical bearing capacity and failure pattern of model clay ground installed by a group of end-bearing as well as floating geopolymer-stabilized soil column (GPSCs) foundations under the embankment loading condition.
- To perform carbon footprint analysis and cost estimation of geopolymer and cement as a binder in DSM technique.
- To perform three-dimensional elastoplastic finite element analyses (FEA) of the ground improved with geopolymer stabilized soil columns (GPSCs) under embankment static loading to validate the model test results.

## **1.8** Organization of the thesis

The current research has been divided into eight chapters, and the outline of the chapters is given below:

**Chapter 1** This chapter provides a brief introduction to the DSM technique for soft soil ground improvement and geopolymer as a sustainable binder in the DSM technique. It also outlines the research objectives, significance, and importance of the present study.

**Chapter 2** This chapter gives preliminary and background information on deep soil mixing techniques, such as applications, installation patterns, installation techniques, and methods. This chapter then includes the literature review part, which includes analytical methods to study the bearing capacity of single and group of deep soil mix columns and critical factors influencing the bearing capacity with the latest advances in DSM techniques and research on the utilization of industrial waste-based geopolymer in civil engineering. In conclusion, research gaps in the available research are identified based on the literature review, highlighting the significance of the current study.

**Chapter 3** This chapter includes the details of the test materials, sample preparation, testing equipment utilized, and experimental procedures. Description of the model setup, instrumentation, static and cyclic load application on the single column and group of columns are also elaborated.

**Chapter 4** This chapter presents the results of the unconfined compressive strength (UCS) test with a focus on different parameters affecting the strength of the geopolymer-stabilized soft soil, pH test, consolidated undrained static triaxial tests, and consolidated undrained cyclic triaxial tests to determine the optimum geopolymer mixture. Microstructure analysis using scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR) and toxicity characteristic leaching procedure (TCLP) test results are discussed.

**Chapter 5** This chapter presents the result of physical axisymmetric model tests conducted on single geopolymer stabilized soil column (GPSC) in very soft soil under static and cyclic loading conditions. The primary parameters examined include the effect of the $l/h$ ratio (end-bearing and floating GPSC) under static loading, the area replacement ratio ($A_r$) under static and cyclic loading, and the effect of CSR under cyclic loading. The static and cyclic behavior of GPSC-treated soft soil at the same area replacement ratio are compared.

**Chapter 6** This chapter discusses the performance of an embankment supported on groups of end-bearing and floating geopolymer stabilized soil columns (GPSCs) in very soft clay under traffic loading conditions. The comparison of the settlement and failure pattern under static and cyclic loading on GPSCs treated soft soil under embankment is done. The primary parameters examined include the loading type (static and cyclic), *l/h* ratio (end-bearing and floating GPSCs), and area replacement ratio ($A_r$). The findings are interpreted in terms of ultimate load intensity ($q_{ult}$), bearing capacity factor ($N_c$), dissipation of excess pore water pressure ($P_{max}$), and stress concentration ratio (*SCR*). This chapter also includes the life cycle assessment of geopolymer in comparison to OPC, showing its benefit in terms of economy, engineering and environment.

**Chapter 7** This chapter deals with the validation of the embankment model on a group of geopolymer-stabilized soil columns (GPSCs) under static loading conditions, as presented in Chapter 6, using three-dimensional finite element analysis with Plaxis 3D software. The parameters validated include the *l/h* ratio (end-bearing and floating GPSCs) and area replacement ratio ($A_r$).

**Chapter 8** This chapter summarises the most important conclusions drawn from this thesis work with a direction of the future scope in this area.