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REVIEW PAPER

Biological perspectives in geotechnics: theoretical developments

Surabhi Jain · Partha Narayan Mishra · Satyam Tiwari · Yijie Wang · Ningjun Jiang · Hirak Ranjan Dash · Ilhan Chang · Ashutosh Kumar · Sarat Kumar Das · Alexander Scheuermann · Thierry Bore

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Abstract The interaction of bio–geosphere dates to the formation of first unicellular microbes on earth. However, it is only relatively recently that the complex biological interactions are observed, characterised, and simulated for its use in the domain of geotechnical engineering. Also, many bioinspired approaches have been utilised in computational geotechnics for optimisation and data analysis process. The living phase present in the soil system hold a bearing on the majority of geochemical reactions and assist in modifying its fundamental and engineering behaviour. It necessitates revaluation and rescrutinisation of the conventional theories and formulations in geotechnical engineering, where soil has always

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S. Jain · S. Tiwari · A. Kumar · S. K. Das
Department of Civil Engineering, Indian Institute of Technology Dhanbad, Dhanbad 826004, Jharkhand, India
e-mail: surabhi1991jain@gmail.com

S. Tiwari
e-mail: satyamtiwarinits@gmail.com

A. Kumar
e-mail: ashubitce@gmail.com

S. K. Das
e-mail: saratdas@iitism.ac.in

P. N. Mishra
Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, Uttar Pradesh, India

P. N. Mishra (✉)
School of Civil Engineering, University of Queensland, St Lucia, QLD 4072, Australia
e-mail: pnmishra@iitk.ac.in; p.mishra@uq.edu.au

Y. Wang
Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China
e-mail: yijie2425.wang@polyu.edu.hk

N. Jiang
Southeast University, Nanjing 211189, Jiangsu, China
e-mail: jiangn@seu.edu.cn

H. R. Dash
National Forensic Sciences University, New Delhi, Delhi 110085, India
e-mail: hirakdash@gmail.com

I. Chang
Department of Civil System Engineering, Ajou University, Suwon-si, Gyeonggi-do 16499, Republic of Korea
e-mail: ilhanchang@ajou.ac.kr

I. Chang
School of Engineering and IT, University of New South Wales, Canberra, ACT 2600, Australia

A. Scheuermann · T. Bore
School of Civil Engineering, University of Queensland, St Lucia, QLD 4072, Australia
e-mail: a.scheuermann@uq.edu.au

T. Bore
e-mail: t.bore@uq.edu.au

been considered as an inert engineering material from biological perspective. To that end, this manuscript provides a critical review on biological approaches used in geotechnical engineering by highlighting the ongoing developments, achievements, and challenges to implement the processes. The review further emphasises the role of biological systems on the alteration of fundamental properties of soils and their consequences on effective stress, strength and stiffness, volume change and conduction properties of soils. Overall, the manuscript provides a basic understanding on the biological intervention in the soil system and the importance of consideration of the fourth phase in the soil system, i.e., the living phase, while describing such interventions.

Keywords Biogeotechnics · Bioinspired approaches · Biomediation · Effective stress · Shear strength · Volume change · Conduction

1 Introduction

Biological activities play a major role in soil formation, degradation/weathering, transportation, alteration of soil minerology and morphology through several biogeochemical reactions. However, traditionally in the discipline of geotechnical engineering, soil has always been considered as an inert engineering material from the perspective of biological consequences, up until the last decade. Recently, the importance of biological activities on the rates of geochemical processes and their impact on the engineering behaviour of soils have been emphasised and analysed (Mitchell and Santamarina 2005; Dejong et al. 2013). The resulting multidisciplinary research area devoted towards the effect of biological pathways on the geotechnical behaviour of soils is termed as *Biogeotechnics*.

The last two decades have witnessed exponentially increasing attention towards numerous biomediated process and their impact and influence on physico–chemical–thermal–electromagnetic properties and strength, stiffness, volume change and conduction behaviour of soils (Dejong et al. 2013; Mishra et al. 2017a, c; Panda et al. 2017; Jain et al. 2021). In addition to biomediation, bioinspiration and biomimicry have also been used to develop solutions for geotechnical infrastructure, monitoring methods and analysis of big data (Simpson and Priest 1993; Das and Basudhar 2006; Muduli et al. 2013; Martinez et al. 2022; Zhong and Tao 2022).

With the volume of literature that's presently available considering biological mediation and inspiration in geotechnics, need for a state-of-the-art review on the subject is imperative. This is because, there exists only a limited number of textbooks that consider biological perspectives in geotechnics. To that end, this review aims to bridge that gap. In the first part of this review (current paper), we lay emphasis on the theoretical considerations that are key to understanding the genesis, underpinning physio–chemo–biological processes, and the consequences of biomediation and bioinspiration in Geotechnical Engineering. This, then, forms the basis for the second part of the review which speaks to the practical applications of biomediation and the monitoring strategies to capture the effects thereof on soil systems. Through these two articles, we make an attempt at critically reviewing and analysing the progress that has been made in the discipline of geotechnical engineering from the perspective of biological considerations and introducing the same in a comprehensive manner to the geotechnical engineering community.

The following diagram demonstrates the organisation of sections across the two articles and highlights the sections that have been covered under the purview of theoretical consideration and advances in biogeotechnics (Fig. 1).

2 Consideration of biological inspired methods in geotechnical engineering

Technology, materials, designs and solutions can either be inspired from (bioinspired) or replicate (biomimicked) principles of natural and/or biological systems. Given the fact that several organisms in the biogeosphere are far more ancient compared to the human civilisation, it is imperative that they have adopted, developed and evolved several mechanisms that have allowed them to survive. Concepts from these mechanisms have been borrowed and applied in the arena of geotechnics forming the core of bioinspired geotechnics. Bioinspired geotechnics, therefore, refers to the research devoted towards developing solutions with inspirations from natural and/or biological systems for addressing geotechnical and

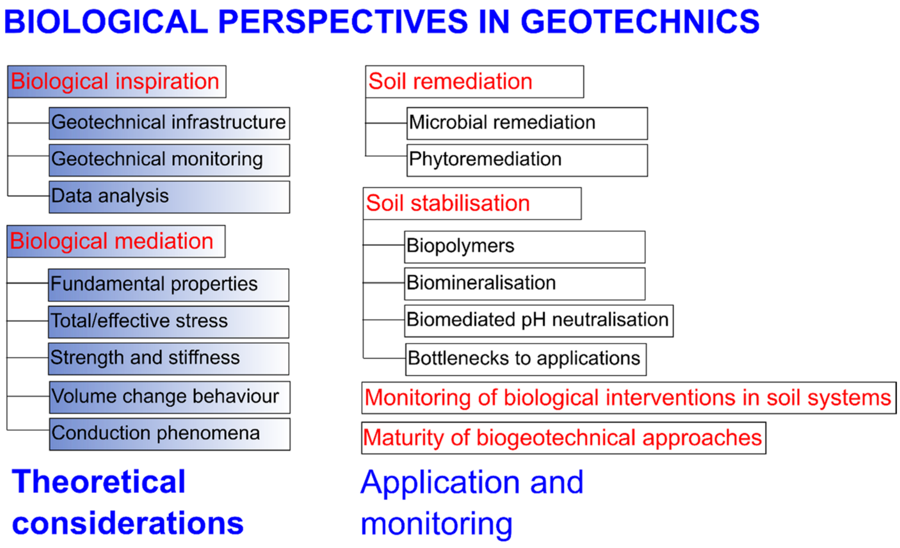

Fig. 1 Organisation of sections in the article with emphasis on theoretical considerations in biological perspectives in geotechnics

geoenvironmental challenges. This section provides a critical review on this emerging field on three aspects i.e. bioinspired geotechnical infrastructure, bioinspired geotechnical monitoring and bioinspired data analysis.

2.1 Bioinspired geotechnical infrastructure

Most of the biologically inspired approaches in geotechnical engineering are either in the preliminary stages of investigations or still undiscovered. Amongst several approaches, the bioinspired burrowing, excavation, and soil penetration are the most energy efficient (Soga 2011). The stability of soil during excavation by an organism depend on soil type, depth, organism size and soil stiffness, etc. (Dorgan 2015; Ruiz et al. 2015). In cohesive soil, the burrowing can be done by rearrangement and aggregation of soil grains whereas in cohesionless soils, it occurs via sand fluidisation technique (Martinez et al. 2022). Both the mechanisms are used by worms, clams, and plant roots (Trueman 1968; Winter et al. 2012; Sharpe et al. 2015; McInroe et al. 2018) and promise a stable excavation (Martinez et al. 2022).

Ants can be regarded as finest engineers since they use less than 1% energy of machines for excavation of same amount of soil (Soga 2011). Researchers have analysed the mechanisms ants use and the configuration of excavation opening (Frost et al. 2017). Discrete element modelling (DEM) and network analysis simulations concluded that the integrated capillarity, friction, and arching mechanism need to be analysed and manipulated for making efficient underground structures (Espinoza & Santamarina 2010). Also, with X-ray image and simulation experiments researchers are trying to understand the movement of large colonies of ants and their used strategies for stable excavation with potential usage in mining and stable tunnel excavation (Frost et al. 2017; Monaenkova et al. 2015). Frost et al. (2017) concluded that the topographical analysis of ant hill can provide details on soil subsurface conditions.

The roots of plants have a penetration resistance and anchorage capacity which depends upon the plant, soil type and environmental conditions (Martinez et al. 2022). Several studies have been conducted to analyse the mechanism of root growth in soil with potential application in infrastructure construction and excavation (Savioli et al. 2014; Shin and Santamarina 2011; Anselmucci et al. 2021; Del Dottore et al. 2018).

An undulation frequency of 5–10 Hz is most efficient for burial work for fish inspired excavation (McKee et al. 2016). Macdonald et al. (2014) concluded that fishes use two phase pumps to liquefy the soil and go for burial work.

The aforementioned discussion suggests that ants, plant roots and fish inspired strategies can be applied in stable excavations. However, upscaling the bioinspired excavation size from millimetre to kilometre is a major challenge for engineers.

Paws and tongues of certain mammals and birds, and the skin of several mammals and reptiles mobilise the required shear resistance in different direction which can be imitated for potential usage in foundations for wind turbines (Martinez et al. 2021). Several shear tests have been conducted to analyse the frictional resistance between soil and snake surface for application in soil anchors, soil nailing and foundation design (Marvi et al. 2013; Huang & Martinez 2020; Martinez et al. 2018; Martinez & O'Hara 2021).

Hydroskeletons and anchorage of various animals and plant roots inspire to utilise their flexible, longitudinal split shell and passive behaviour for load transfer mechanism (Mallett et al. 2018; Aleali et al. 2020). This helps in increasing the shaft and ultimate capacity compared to conventional pile designing. Several laboratory, centrifuge, field studies and numerical simulations have also been conducted to understand the load transfer mechanism of plant roots which is helpful in designing the foundation and anchorage system more efficiently than conventional methods (Burrall et al. 2020; Mallett et al. 2018; Aleali et al. 2020). Though finite element modelling infers the bioinspired approach is feasible for pile designing, prototype tests need to be undertaken before implementing the strategies in practical applications.

The stability of natural and manmade slopes, transfer of heat and water in soil system are the major challenges to geotechnical engineers (Martinez et al. 2022), which can be mitigated by various bioinspired approaches. The water removal capacity of plants by their roots increases the soil suction and provide hydraulic reinforcement to the soil (Hemmati et al. 2012). Vegetations alter the suction during wetting and drying, soil–water retention curve, which helps in reduction in hydraulic conductivity and enhance slope stability (Ng et al. 2013; Leung et al. 2015; Switala & Wu 2018).

Termite mounds are built in a way such that it is 10–15 °C warmer and cooler during the night and day, respectively (Turner & Soar 2008). The mounds made by termites can be used as an inspiration to comprehend the approaches for design thermally regulated infrastructure with locally available soil (Zachariah et al. 2017; Katariya et al. 2018; Vesala et al. 2019). A detailed review on the bioinspired mechanism for several infrastructures solution has been presented in Martinez et al. (2022). However, the major challenges faced during in situ implementation of bioinspired infrastructure are, (a) analysing the complex nature of biomaterials which also get altered with time and environment, (b) the difference in soil size and depth where the biological interaction works and engineers need to construct, (c) spatial and temporal variability of the proposed solution during upscaling.

2.2 Bioinspired geotechnical monitoring

Considering the spatio-temporal variability of soil properties and influence thereof on structures made with or on top of them, it is important to have a monitoring regime in place to track the health of soil systems over time. To that end, three pillars underpin a typical monitoring regime i.e. (a) sensors/probes that collect data (b) systems that transmit data and (c) approaches to analyse the data. In this section, we will place our attention on data collection and data transmission approaches inspired from biological systems.

Majority of the in-situ testing methods in Geotechnical Engineering rely on inserting a probe into the ground, and then using the resistance of soil to the insertion as an indicator of soil strength (e.g. standard penetration test, cone penetration test, shear vane test etc.). In recent days, several researchers have considered mimicking the locomotive behaviour of organisms such as earthworms to develop site characterisation probes that are capable of self-penetration (Martinez et al. 2020; Chen et al. 2021). They observed that the self-penetration resistance is higher in dense sands compared to silts and clays. Through DEM modelling on non-cohesive soils Chen et al. (2021) observed that the favourable conditions for self-penetration were (a) shorter anchor-tip distances (b) long anchors with high expansion magnitudes and friction coefficients. This innovation has the potential for development of light weight rigs that will allow characterisation of sites with limited accessibilities. A similar self-burrowing device taking inspiration from root growth and fluidisation of granular medium has also been reported in the literature (Naclerio et al. 2018).

Piezoelectric sensors find wide applications in geotechnical engineering (Zeng 2006) due to their versatility to measure changes in several variables such as temperature, pressure, force, and acceleration based on the principles of piezoelectric effect.

In fishes, sensory organs called neuromasts are used as pressure sensitive flow detectors. Each neuromast houses a copula that is sensitive to the water motion on the body of the fish. The nerve impulses are then carried via a nerve fibre to the brain of the fish. Similar principle applies to piezoelectric water pressure sensors that respond to changes in water pressure (Tuhtan et al. 2020). Figure 2 demonstrates a piezoelectric sensor for monitoring water pressure and how it derives inspiration from the lateral-line system of fish.

Once the sensor obtains the required data, the next step for monitoring is to transmit this data to a server or a system for visualisation, post processing and analysis. The data transmission system may be wired or wireless, with a continuously increased interest and infrastructure towards supporting the latter. Bioinspiration also assists in design of such communication systems (Atakan et al. 2009). Recently, Zhong and Tao (2022) developed a vibration based underground communication system, where the bioinspiration aspect of the development was hinged to the mechanical wave transmission by subterranean and some surface-dwelling animals through biological tremulation and drumming. They found that the developed system could transmit information to a distance of 80 cm in dry and medium dense sand in the laboratory conditions. The final step of monitoring is linked to analysis of the retrieved data. Bioinspired approaches for data analysis are discussed in the later section of the manuscript.

From the discussion above, it is evident that bioinspiration is a credible source to develop geotechnical monitoring systems that capture the processes of development of sensors and data transfer.

2.3 Bioinspired data analysis

The development of computational geomechanics has closely followed the development in computational mathematics. Biological processes have always inspired scientific thinking. Accordingly, development in mathematics and physics have followed natural phenomena. The Fibonacci number explains the growth of rabbit populations and the golden section ratio explains some human features. In 1936, Alan Turing used biological inspiration to develop a machine named Turing machine, which was the precursor of modern-day computer (Turing 2009). The motivation of nervous system to solve logical calculus by McCulloch and Pitts (McCulloch and Pitts 1943) was the beginning of artificial neural networks (ANN). Though, Rosenblatt (Rosenblatt 1958) encouraged it with hypothetical perceptron, but Minsky and Papert (1969) reported the limitations. Finally, after the proposal of the parallel distributed processing with inspiration from the neural system by Rumelhart et al. (1988), the ANN and its variants were developed to be used different branches of science and engineering.

The development of evolutionary algorithm (EA) took flight in the 1970s when genetic algorithm (GA) was introduced by John Holland in 1975 (Holland 1992). This may be considered the first algorithm to use crossover and recombination in optimisation and sequence modelling. The approaches based on the intelligence of the population gave birth to genotype, genetic code and self-adaptation. In the 1990s, innovative works on nature-inspired algorithms and memory-based metaheuristics took place with published works on ant colony optimisation (ACO) and tabu

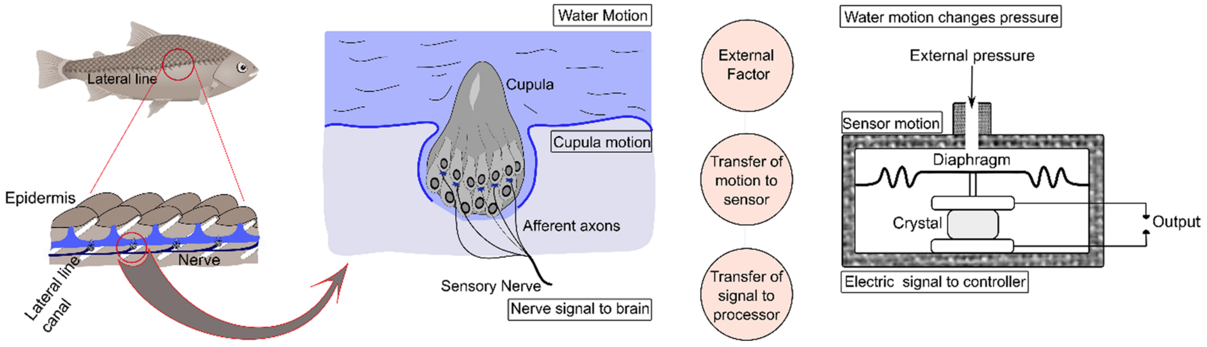

Fig. 2 Schematic of a piezoelectric sensor with inspiration from the lateral line system of fish

search (Glover and Laguna 1998). American psychologist James Kennedy along with engineer Russell C. Eberhart came up with the concept of particle swarm optimisation (PSO) (Kennedy 2006) inspired by the swarm intelligence of creatures like fish, birds, and even humans. Initially, the algorithms were focused only on the human brains and cognitive ability, but with time paradigm shifted towards a much wider scope of organisms, processes and phenomena observed. This shift was observed from the development of the harmony search (HS) algorithm (Geem et al. 2001), artificial bee colony (ABC), Firefly algorithm in 2008 (Yang 2010), cuckoo search (CS) algorithm (Yang 2010) and many others. In the subsequent years, a vector-based evolutionary algorithm named differential evolution (DE) was developed.

GA has been used in geotechnical engineering since 1990's (Simpson and Priest 1993) and at that time there were also attempts for development of ANN modeling to complex geotechnical systems like soil liquefaction, pile foundation etc. to replace the statistical based empirical methods (Goh 1994). To avoid the limitation of ANN as a "black box", prediction model development with inspiration from genetics through genetic programming (GP) (Koza 1992) and its variants are being used in artificial intelligence (AI) and machine learning (ML) based computer programming. This mini review aims at providing a systematic introduction to biologically inspired algorithms, their source of inspiration, their developmental aspects and applications restricted to geotechnical engineering problems and future challenges. The review is divided into two categories: bio-inspired optimisation algorithms and artificial Intelligence based classification/prediction algorithms.

2.3.1 Optimisation techniques

Though the history of optimisation can be traced back to the seventeenth century to the times of Newton and Leibnitz, most of the traditional optimisation methods were developed after the 1940's for the reconstruction of war devastated world. Nature itself contains a lot of examples of biological phenomena that inspire the new set of optimisation algorithms. Darwin's theory of survival of the fittest and evolution of the species is the best example of an optimisation process. GA by John Holland in 1975 (Goldberg 1989) is the first bioinspired optimisation tool. Bio-inspired optimisation algorithms can be divided into three groups based on the nature of their biological inspiration. i.e. (a) swarm intelligence algorithms, (b) evolutionary algorithms (EAs) and (c) bacteria foraging algorithms.

2.3.1.1 Swarm intelligence algorithms The concept of swarm intelligence was proposed by Beni and Wang in the 1990s (Beni and Wang 1993). Global swarm intelligence is developed by the interaction of individual agents, and there is no global control system to dictate an individual's behaviour (Kennedy 2006). As depicted in Fig. 3, these algorithms take motivation from animals, insects, or other biological species' behaviour. Some examples of swarm intelligence are ant colonies, bee colonies, bacteria growth, bird flocking, fish schooling, cuckoo search and firefly techniques (Kumar and Kumar 2021).

Taking inspiration from the concept of stigmergy, a term crossed by Grass in 1992, ant colony optimization (ACO) method was introduced by Dorigo in 1992. The type of colony-level behaviour used by ants to find the optimal path between their nest and food source is the source of the ACO optimisation algorithm. A schematic representation of the ACO mechanism is shown in Fig. 3 where all the possible paths are crawled by the ants randomly at the start and an optimal path is discovered with time.

Particle swarm optimisation (PSO) is another swarm optimisation algorithm loosely inspired by the social stigma of bird flocking. The mechanism of PSO can be understood by the virtual image of a bird flock searching for insects as their food (Kennedy 2006). The bird with a greater number of insects in its neighbourhood cries louder in comparison to a bird with a lesser number of insects in its neighbourhood. PSO consist of a particle group that collectively moves over the search space to reach a global optimum (Fig. 3b) (Floreano and Mattiussi 2008).

Cuckoos lay their eggs in the nests of other species/host birds and may also remove eggs of that species. As cuckoos' eggs hatch earlier than host birds' eggs, they increase their share of food. Figure 3c shows the mechanism of transfer of cuckoo eggs with good fitness value (good solutions) to the next generation and the cuckoo search algorithm (CS) (Yang 2010).

The bee colony optimization (BCO) was originally introduced by Pham et al. (2013) is inspired by the

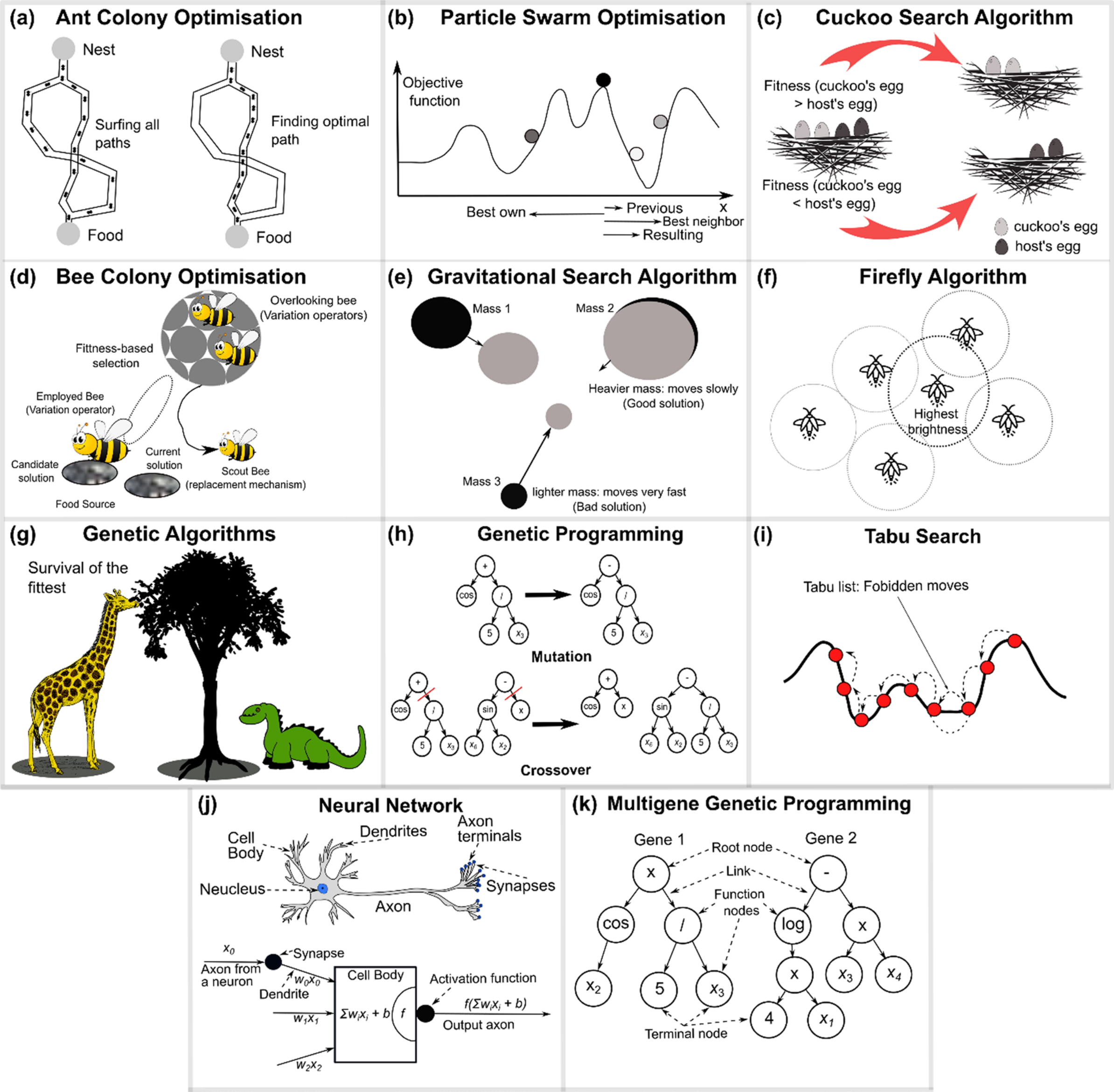

Fig. 3 Schematic diagram showing bioinspiration in **a** ant colony optimisation, **b** particle swarm optimisation, **c** cuckoo search algorithm, **d** bee colony optimisation, **e** gravitational search algorithm, **f** firefly algorithm, **g** genetic algorithm, **h** genetic prog/ramming, **i** tabu search, **j** neural network, **k** multigene genetic programming

food foraging behavior of the colonies of honeybees. For a particular problem, the bee algorithm thinks about all its candidate solutions as food sources, similar to flowers for bees. The solution space is searched with the help of a population of n number of agents mimicking bees. The profitability of a solution is evaluated by agents (bees) every time they visit a solution (flower). A process flow diagram of fitness-based selection of BCO is shown in Fig. 3d, where current and candidate solution space are explored by bees based on the fitness value.

Intelligent water drops (IWD) algorithm is a swarm-based algorithm for optimisation problems. The motivation is based on gravitational pull of water drop in a river that flows in a straight line (shortest path) towards the lake or the ocean if no barrier is present (Al Deeb et al. 2014). In contrast, water drops keep modifying the real path to avoid obstruction and approach more towards the ideal path (Hosseini 2007).

The gravitational search algorithm (GSA) is based on the gravity law of Newton which states that every existing particle attracts other existing particles with a pull that is directly proportional to the masses of particle and inversely proportional to the square of the separation between them (Rashedi et al. 2009). The exploitation of the algorithm is guaranteed by the slow movement of heavy mass (good solution) in comparison to lighter mass (bad solution) (Fig. 3e) (Rashedi et al. 2009).

In coral colonies, these corals grow and reproduce by choking out neighbouring corals for space. This fight for survival and some unique characteristics of their reproduction is the inspiration for development of Coral reef optimisation algorithm (CRO) (Salcedo-Sanz et al. 2014).

The beautiful sight of sort and rhythmic flashes of light of the fireflies is the motivation for fire fly algorithm (FA). The brighter lights attract more mating partners and more prays (Fig. 3f) and the algorithm is based on this flashing characteristics (Kumar and Kumar 2021).

2.3.1.2 Evolutionary algorithms (EAs) The EAs are population-based approach with a number of potential trial solutions and the motivation is survival of the fittest. These solutions go through various alterations with terminologies; reproduction, crossover and mutation, derived from genetics. Two most widely used EAs are genetic algorithms (GA) and differential evolution (DE).

GA uses directed random searches for the location of optimal solutions in difficult terrains of solutions. GA mimics the evolution process of nature to find a set of the solution then it alters the pool of solutions by using the biological operations of mutation, crossover, and selection makes it a truly bio-inspired algorithm. The concept of GA, as represented in Fig. 3g is based on the idea that a specie (solution) which is having more chances of survival (like giraffe in this case, as it can procure food even from higher branches of trees) will get transferred to next generation of population.

2.3.1.3 Bacteria foraging algorithms DE works with the same steps as a standard EA but individual trial solutions are referred to as genomes, unlike traditional EAs, the objective space in DE is explored based on the difference of genomes (Das and Suganthan 2010). Bacterial Foraging optimisation algorithm (BFO).

The foraging strategy is the method of locating food, its handling and at the end ingesting it. Natural selection favours the growth of animals with good foraging strategies. Such evolutionary theories are the motivation towards exploration of the possibility of modelling these foraging strategies as optimisation processes. Passino introduced Bacterial foraging optimisation algorithm (BFO) that mimics the foraging behaviour of E. coli bacterium (the one present in our stomach).

Some other bioinspired optimisation algorithms, which are based on bio-inspiration are Tabu search (TS), and Runner-root algorithm (RRA). The meaning of 'Tabu' is related to the sacred things which cannot be touched. It keeps a short-term memory of several set of solutions. In TS cycling is prevented by maintaining a list of tabu solution, which are forbidden to be touched (just like the meaning of name Tabu) (Fig. 3i). The basic concept of this kind of search is to restrict moves that wants to revisit already searched spaces (Glover and Laguna 1998). The RRA is inspired by the runners and roots of a plants like strawberry and spider in nature. These plants propagate through the runners in the environment, at the same time they develop their root hairs to locally search for food (water and Minerals) for their development. The unique nature of the RRA comes from the fact that it performs global search to reach an optimal solution in all its iterations, apart from that, it also performs local search, only in the condition when global search fails to improve the cost function value (Merrikh-Bayat 2015).

The list of some bio inspired algorithms with basic principles and their applications in geotechnical engineering in a comprehensive manner is presented in Table 1.

2.3.2 Artificial intelligence based classification/prediction/clustering algorithms

2.3.2.1 Neural network (NN) The idea of NN was first introduced by McCulloch and Pitts in 1943 and finally developed by Rumelhart et al. (1988). The NN

Table 1 List of bio-inspired optimisation algorithms

Algorithm	Biological inspiration	Application in geotechnical engineering
Swarm intelligence techniques		
Ant colony optimisation (ACO)	Ant's food search mechanism	Design of reinforced concrete retaining wall (Hajihassani et al. 2018) Piled raft foundation (Hajihassani et al. 2018)
Particle swarm optimisation (PSO) (Kennedy 2006)	Bird flocking search for food	Correlation of shear strength parameters with rock index (Hajihassani et al. 2018) Calibration of soil modeling parameters (Hajihassani et al. 2018) Slope stability analys (Hajihassani et al. 2018)
Cuckoo search algorithms (CS)	Obligate brood parasitism	Slope stability analysis (Gandomi et al. 2017a)
Bee colony optimisation (BCO) (Pham et al. 2013)	Food foraging behavior of the bees	Soil parameter estimation (Samui et al. 2019) Foundation and retaining wall problem (Zhao et al. 2016),
Intelligent water drops (IWD) (Hosseini 2007)	Natural water drops flowing in rivers	Nil
Gravitational search algorithm (GSA) (Rashedi et al. 2009)	Gravitational law of Newton	Deformation in soil structures (Momeni et al. 2021) Bearing capacity prediction of piles (Harandizadeh et al. 2019) Spread foundation construction (Khajehzadeh et al. 2014a)
Coral reef operation algorithm (CRO) (Salcedo-Sanz et al. 2014)	Coral reefs' formation and reproduction	Nil
Firefly algorithm (FA) (Yang 2010)	Firefly's flashing characteristics	Optimum design of reinforced concrete foundation (Khajehzadeh et al. 2013) Retaining walls (Sheikholeslami et al. 2016) Analysis of slope stability (Kumar and Kumar 2021) Early warning system to mitigate seismic hazards (Ebid 2021) Soil thermal conductivity prediction (Kardani et al. 2021) Unconfined compressive strength prediction of soil (Cao et al. 2021)
Evolutionary algorithms (EAs)		
Evolutionary programming (EP) (Fogel 2000)	Theory of evolution (crossover and selection)	Analysis of slope stability (Gao 2015) Soil modeling (Javadi and Rezania 2009)
Differential evolution (DE)	Theory of evolution	Slope stability prediction (Das et al. 2011) Parameter identification (Vardakos et al. 2012) Prediction of jet grouting column diameter (Njock et al. 2021)
Genetic algorithms (GA) (Holland 1992)	Theory of evolution (mutation, crossover and selection)	Probabilistic finite element analysis (Cui and Sheng 2005) Parameter determination for constitutive modeling (Samarajiva et al. 2005) Critical slip surface (Goh 2007) Foundation pit deformation modeling (Ebid 2021)

Table 1 (continued)

Algorithm	Biological inspiration	Application in geotechnical engineering
Bacteria foraging optimisation algorithm (BFO)	Swarm and bacteria foraging behaviour	Optimal design of reinforced concrete cantilever retaining wall (Ghazavi and Salavati 2011)
Other bio-inspired optimisation algorithms		
Tabu search (TS) (Glover and Laguna 1998)	‘Tabu’ based search	Slope stability slip surface identification (Cheng et al. 2007) Soil liquefaction potential evaluation (Ahmad et al. 2021)
Runner-root algorithm (RRA) (Merrikh-Bayat 2015)	Runners and roots of a plant in nature	Nil

is a collection of nodes and units which are connected, these nodes are artificial neurons which mimic the neuron in the biological brain. As described in Fig. 3j, the neural network consists of connections that transmit signals to other neurons, just like the working of synapses in brains. These signals are transferred to other connected neurons, and the output computation at each neuron is done using the non-linear function of the summation of their inputs. These connections are mimics of axons. These neurons and edges have some weights attached to them which change as learning proceeds, these weights are responsible for increase and decrease of signal strength at a connection. There are various types of NN based on the type of architecture.

2.3.2.2 Genetic programming (GP) Genetic programming (GP) is a technique in which an initial unfit population is evolved with the application of operations that are analogous to natural processes of genetics (Koza 1992). These operations involve selection of the fittest population for performing crossover (reproduction) and mutation. Some members are directly promoted to the next generation, called elitism. The basic mutation and crossover operations are the primary elements of GP (Fig. 3h. The other variants of GP are Multigene genetic programming (MGGP) (Fig. 3k), linear genetic programming (LGP) etc.

2.3.2.3 Other evolutionary prediction models The Evolutionary polynomial regression (EPR) constructs symbolic models by utilizing a two-stage technique which involves structural identification and estimation of parameters (Rezania et al. 2010). The evolutionary programming (EP) (Fogel 2000) is based on the process that can generate population of increasing intellect over time. The artificial immune system (AIS), introduced by Jeffrey O. Kephart in 1994, is a rule based computationally intelligent system and is modeled based on the characteristics of memory and learning for the use in problem solving.

The applications aspects and comprehensive review of AI method can be found in Das (2013) and (Ebid 2021) and a brief review is presented in Table 2.

3 Role of biological activities on the fundamental properties of geomaterials

Soils exhibit a great degree of spatio-temporal variability pertaining to grain size, shape, mineralogical and chemical composition that further influences their engineering behaviour. Geotechnical engineers often need to evaluate the properties of the soil mass for its usage in a particular design or construction. Analysing these soil properties needs a basic understanding of the characteristics of the material and the processes it has undergone to reach its present state (Mitchell and Soga 2005). This demands identification and appreciation of the geochemical process involved in a soil system since its genesis. The abundance of biomass on the soil surface and subsurface assist to realise the contribution of microorganisms, plants, and their biological activity on the alteration and acceleration of geochemical reaction (Mitchell and Santamarina 2005); the biogeochemical reactions

Table 2 List of bio-inspired artificial intelligent algorithms

Algorithm	Biological inspiration	Application in geotechnical engineering
Artificial immune system (AIS)	Vertebrate immune system	Nil
Neural networks (NN) (Rumelhart et al. 1988)	The brain	Load capacity prediction in piles (Das and Basudhar 2006) Shafts drilling (Goh et al. 2005) Constitutive modeling of geomaterials (Ebid 2021) Foundation settlement (Das 2013) Retaining walls (Ebid 2021) Site characterisation (Ebid 2021) Slope stability analysis (Das 2013)
Genetic programming (GP) (Koza 1992)	Theory of evolution (mutation, crossover, and selection)	Settlement characteristics (Shahin 2015) Bearing capacity prediction (Shahin 2015) Liquefaction mechanism of soil (Muduli and Das, 2015b) Constitutive modeling of geomaterials (Javadi and Rezania 2009; Shahnazari et al. 2010; Feng et al. 2006) Deformation moduli, shear strength, frictional strength, shear wave velocity etc. (Rashed et al. 2012; Shahnazari et al. 2013)
Multigene genetic programming (MGGP) (Koza 1992)	Theory of evolution (mutation, crossover and selection)	Prediction of pile load capacity (Muduli et al. 2015) Estimation of foundation settlement (Das 2013) Soil liquefaction potential (Muduli et al. 2014; Muduli and Das 2014, 2015a) Model soil behavior (Ebid 2021) Fly ash permeability (Garg et al. 2015)
Evolutionary polynomial regression (EPR)	Theory of evolution	Material modeling of different soils (Faramarzi et al. 2012) Correlation between soil properties (Jin and Yin 2020) Liquefaction potential (Ghorbani and Eslami 2021) Compressibility and permeability of soil (Yin et al. 2016) Stress–strain relationship of municipal solid waste (MSW) (Ebid 2021)

accelerate major nutrient movements and alter the soil behaviour to a great degree.

Various biogeochemical process involved in the ecosystem can be divided into two major categories i.e., gaseous and sedimentary cycles. The gaseous cycles include carbon, oxygen, nitrogen and water cycles, whereas sedimentary cycles involves sulphur, phosphorus and rock cycles.

In oxygen and carbon cycle, not only plants but also the photosynthetic bacteria (cyanobacteria) forms cellular carbon and, molecular oxygen from water and carbon dioxide (Mitchell and Santamarina, 2005). These microbes alter the pH of pore water, due to formation of carbonates. Also, they assist in soil weathering. Various soil microbes undergo different metabolic processes and help in nitrogen fixation, nitrification and denitrification. These three mechanisms are the major components in nitrogen cycle where nitrogen converts to different forms present in soil. Soil micobes partake in oxidation and reduction and help transfer the nutrients in different forms that further alters the soil composition. For example, microbes play an important role in sulfate oxidation, sulfide reduction and iron oxidation, that ultimately change the soil behaviour. A detailed diagram of involvement of microorganisms on nutrient movement/cycle in ecosystem is presented in the Fig. 4.

The change in the chemical composition, pH, cation exchange capacity (CEC) and surface characteristics of soils are usually the chemical properties of interest. Some of the key soil physical properties include grain size, shape and specific gravity. Biological activities alter these chemical and physical properties via influencing and accelerating the rock and soil weathering, erosion, transportation, and deposition process.

Biological weathering is one of the important geochemical processes during which the geomaterial undergoes alteration in its size, shape, and composition. Biological weathering includes mineral dissolution and breakdown/degradation of soil particles due to the growth, metabolic activity and degradation of

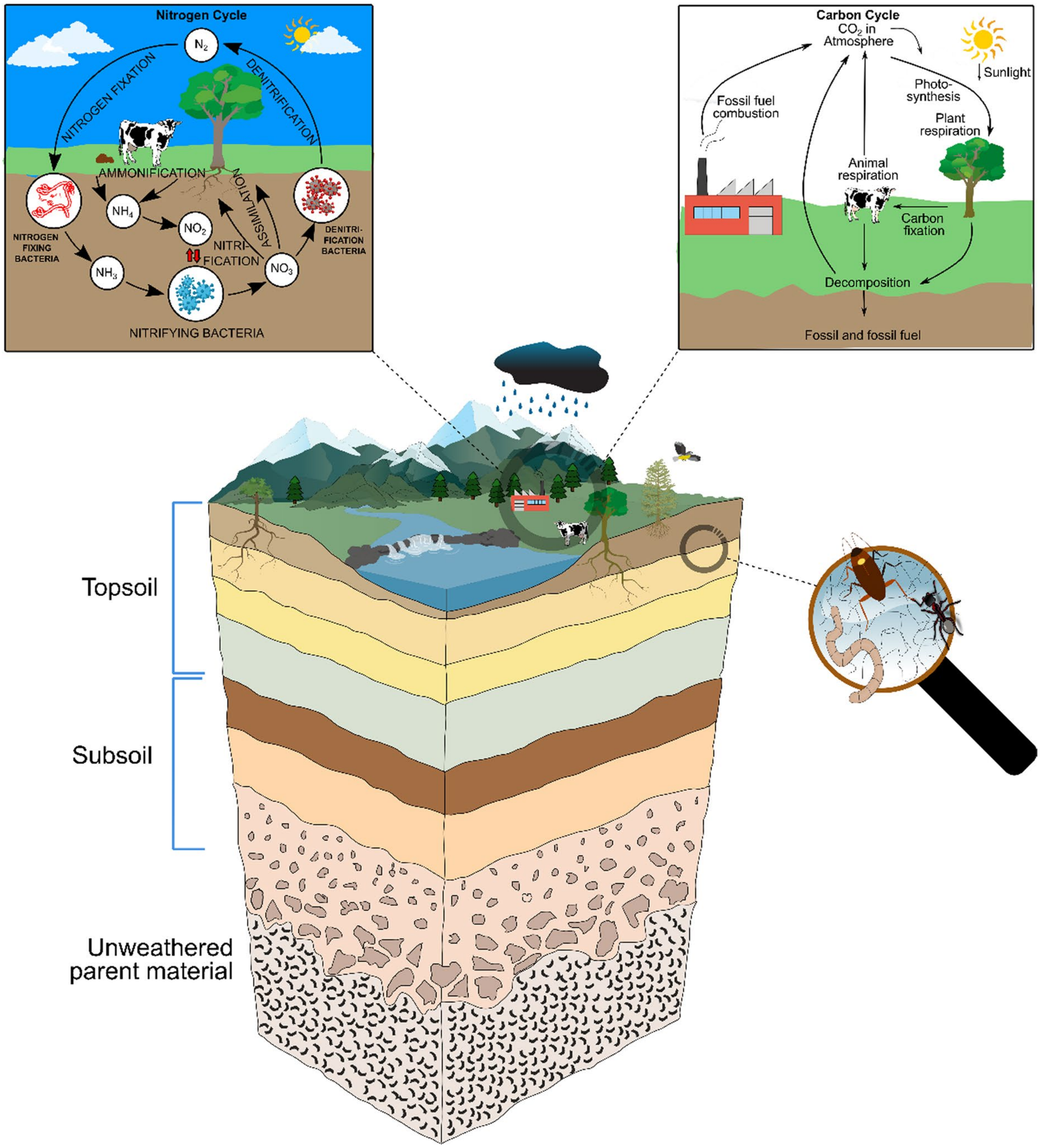

Fig. 4 Interaction amongst geosphere, hydrosphere and biosphere in sustaining major nutrient cycles

various plants, a wide variety of microorganism, and other organisms. Among them, microbial weathering is a complex interaction of the diverse microbial species present in soils, rocks and minerals. The common approaches used to comprehend the microbial weathering is either investigating the weathering process by a single microbial species/ defined mixed microbial culture or by examining the microbial activity for a particular rock mineral (Kelly et al. 2016). Several laboratory and field studies have been carried out to investigate different microbial weathering mechanisms (Gadd 2010). Though microbial weathering process is often considered from the perspective of fundamental microbiology or geology, identifying and analysing individual mechanism and the weathering process in terms of engineering perspective is necessary to harness it in other field of applications such as bioleaching and bioremediation. For instance, Vera et al. (2013) have excellently reviewed the progress of bioleaching by understanding the bacterial metal iron sulphide oxidation process.

The basic microbial metabolic processes which directly alter soil physio–chemical properties and contribute to weathering are: Metal chelation, pH alteration, oxidation and reduction.

3.1 Metal chelation

Metal chelation forms new complexes via bonding the ligands with metal ions present in a system. The production of organic acid due to various microbial metabolic activities accelerate the dissolution of various minerals from soil and rock (Saad et al. 2017). This organic acid also acts as a ligand, binding the released heavy metals and precipitating soluble or insoluble complex mineral (Konhauser 2006). The precipitation of new mineral decreases the saturation state of metal in solution and assists in release of more metals from the soil mineral. Experiments show that production of 3,4-Dihydroxybezoic acid (DHBA) via microbial activities can dissolute numerous feldspar minerals. During this process, the acid dissolutes a wide range of metal cations and form various complexes. The microbial activities produce siderophores, having a higher metal affinity compared to organic acids, that bind with various metals such as iron, copper, manganese, nickel, etc. and form respective products (Konhauser 2006). The dissolution of other complex metals and ligand-based mineral formation via various microorganisms are still being researched (Saad et al. 2017).

To summarise, microbial metal chelation assists in the processes of weathering, disintegration and formation of new mineral which further impacts the grain size, surface area, surface charge, density, and surface area of soils. However, not many studies have been conducted to relate the effect of weathering on soil size and nature of soil, which remains as a scope for future research.

3.2 pH alteration

The microbial growth and metabolic processes either increase or decrease the surrounding pH which has a bearing on the weathering process (Konhauser 2006). Most of the microbial community produce organic acid as their primary and secondary metabolic product by oxidising the carbon source to acid such as amino acid, lactic acid and citrate (Willey et al. 2008). Release of these acids influence the dissolution, disintegration of rock and alter the pH of the soil system. Oxalic acid, one of the widely encountered organic acid produced by fungi act as a weathering agent in the calcareous soil (Thorley et al. 2015). Not only the organic acid production, but also the release of carbon dioxide during microbial respiration also interacts with water to produce carbonic acid. Carbonic acid is hinged to various mineral weathering process including dissolution of carbonates (Thorley et al. 2015).

The production of various acids helps to split the Si–O–Si and Al–O–Si bonds, weakens the minerals in soil matrix and accelerates the mineral dissolution. This acidolysis process is one of the most significant microbial weathering processes, since acids also help to displace other metal cations such as iron, aluminium, potassium, etc. from the aluminosilicate minerals and release into the system solution (Gadd 2010). The pH mediated and ligand-based weathering due to acid production can occur simultaneously. However, their impact on mineral dissolution rate varies with rock type and concentration of acid production (Gadd 2010). The production of various inorganic acids (such as sulfuric and nitric acid) and acidic/basic exopolymeric substances (EPS) due to microbial redox reactions also change the pH of the surrounding soil system. Various acidic EPS have the ability to weather feldspar in a 50 to 100-fold faster than abiotic weathering (Welch et al. 1999). The EPS molecules also act as ligands and bind the silicon and metals leached from the soil or rock mineral. Pertaining to pH increase, photosynthetic microbes produce carbonate anions and raise the pH of soil–solution mixture which help to leach various elements such as Ca, Mg, Si and K from the soil or the parent rock. Hence, it leads to soil and rock weathering process by raising the pH (Olsson-Francis et al. 2012).

The high generation rate, mutation, faster adaptability to the new ecosystem enables the survival of microbes in extreme soil pH conditions (Mitchell and Santamarina 2005; Willey et al. 2008). Understanding the prevailing biochemical processes associated with pH alteration assists to simulate the same for modifying the soil behaviour for engineering applications. Panda et al. (2017) isolated some native microbes from bauxite residue (red mud) and fed them with dairy waste to reduce the alkalinity of red mud from the pH value of 11.5 to 7. The bio-neutralised red mud was further characterised pertaining to its geotechnical properties for its efficient utilisation in embankment material. Levett et al. (2022) analysed the natural biogeochemical process of formation of natural iron cement and utilised the same for stabilising, remediating the iron ore mining area and doing revegetation.

3.3 Oxidation and reduction

Microorganisms need energy to sustain life like any other lifeform. The chemotrophs gather energy during the oxidation process where a compound loses energy by providing its electron to an electron receiver. During this, oxidation–reduction process occurs simultaneously and facilitate the weathering process of soil.

The sulfate oxidation and sulfide reduction which mostly occurs in combination with iron reduction and oxidation has been studied thoroughly by considering its effect on soil properties, weathering, acid mine drainage (Chapelle 2001; Mitchell and Santamarina 2005). In anaerobic condition, the presence of wide range of sulfate reducing microbes reduce sulfate to sulfide. In aerobic condition, the sulfide oxidising microbes helps to convert sulfate (Chapelle 2001). Similarly, the iron is present in the subsurface in the form of ferrous or ferric state and it undergoes oxidation reduction process via various iron reducing microbes such as *Thiobacillus species*. In the combined iron and sulfur oxidation i.e., during pyrite oxidation, the *Acidothiobacillus ferrooxidans* produce oxidised sulfur compounds such as thiosulfate and sulfuric acid. This acid production is the main source of acid mine drainage and influence the weathering process significantly. Li et al. (2014) showed the sulfuric acid production during pyrite oxidation reduced a bulk rock pH to acidic (pH = 2.5) from neutral (pH ~ 7). The microbial redox reaction alters the pH and the pH also influence the kinetics of redox reaction (Hedrich et al. 2011). Though the pyrite oxidation occurs in abiotic conditions, the microbial oxidation increases its rate 10–20 times.

Iron oxidation combined with pyrite weathering is one of the examples of geological weathering. Similarly, several metallic and non-metallic elements such as iron, manganese, copper, carbon, nitrogen, phosphorous undergo oxidation–reduction process via different microbial communities and helps in weathering of minerals (Gadd 2010). Different strains of *Pseudomonas putida, Bacillus subtilis* are found in wide geological environments which reduce manganese from rhodochrosite ($MnCO_3$) and form birnessite (MnO_2) (Carmichael et al. 2013). The oxidation of organic matter also occurs via various microbes to gather energy that helps in weathering of organic material present in soil, rocks, coal, shales (Berlendis et al. 2014).

The biogeochemical cycles of weathering can occur in the environment as an isolated process or an interconnected process involving diverse microbial metabolic process by supporting one another's growth. Both microbially induced (i.e. directly contributing to weathering) and microbially influenced (i.e. influencing abiotic weathering) significantly change the physical and chemical behaviour of soil from microscopic level to macroscopic scale.

Many of the weathering processes also contribute to the erosion of soil and rock up to a certain extent. For example, EPS and biopolymers affect the rate of erosion. Besides, some pure bio-erosive processes also exist such as the fungal hyphae growth that has the ability of splitting the mineral plane (Hutchens 2009). These bio-erosive processes break the geomaterials altering the soil size and shape but does not affect its chemical properties much.

Although microbes are involved in various geochemical cycles, the occurrence of these processes is dependent on the survivability of microbes in the soil pores

(Mitchell and Santamarina 2005). Bacteria need a pore size greater than 4 µm, whereas fungi and protozoa need a size greater than 6 µm. Some of the microbes live in colonies and/or symbiotic communities with other species, which require more space to survive and undergo their chemical process. In this regard, coarse-grained soils provide enough pore space in which bacteria can adhere to the mineral surface via forming colonies or biofilms and EPS. These EPS and biofilms accelerate many chemical reactions and help in weathering and erosion processes. Though the effect of the microbial process on the formation of coarse-grained soil is minimal, various bioactivities occur and influence the surface properties and interparticle contacts which need a comprehensive study. In fine-grained soil, microbial activities play an important role in the formation since it facilitates nucleation and crystal growth (Mitchell and Santamarina 2005). A comprehensive study on bio-related sediment formation, the involved mechanism, time, and size scales is presented in Mitchell and Santamarina (2005).

The above discussion highlights the involvement of microorganisms and the influences of their biochemical process in altering the basic physico–chemical properties of soil that has a consequential impact on the engineering behaviour of soils. Although various biomediated process are being used in recent days to alter the engineering behaviour of soil, only a few studies emphasise the effect of the biochemical process on the fundamental properties of soils. An in depth understanding of soil-microbe interaction in different environmental conditions could provide more knowledge on the same and can further assist in engineering the Biomediated pathways to generate solutions for geoengineering challenges. An example of utilising a bioprocess in altering the soil physical i.e. consistency behaviour is by utilising microbes or plant-based biopolymers. Studies have shown that the addition of biopolymers alter liquid limit of soils since the process imparts a viscosity to the pore fluid. In case of expansive clay minerals (e.g. montmorillonite) the addition of xanthan gum reduces the liquid limit by changing the surface charge and particle aggregation (Chang et al. 2020).

4 Consideration of biological actuation and influence on geotechnical behaviour

The evolution of geotechnical engineering as a subject started with consideration of physical laws governing soil behaviour, which was then extended to include chemical influences. Consideration of biological actuation and influence in the framework of geotechnical engineering is a relatively recent development. While such considerations are often described in qualitative terms, limited attempts have been made for development of theoretical formulations in geotechnical engineering to incorporate these considerations. This section summarises such considerations, underlying mechanisms and then proposes several theoretical formulations pertaining to stress, strength, volume change and conduction phenomena in soils that integrate the biological effects on the soil system.

4.1 Total/effective stress

Development of the concept of effective stress dates back to eighteenth century with initial descriptions by Charles Lyell, followed by works from Boussinesq, Reynolds, Föppl and Rudeloff, and Fillunger (de Boer and Ehlers 1990). de Boer and Ehler (1990) report that several of Fillunger's work has also supported the development of the effective stress principle. They write,

> "It is difficult to believe that von Terzaghi should be the only one who discovered the idea of effective stress, if one considers Fillunger's total work on the mechanical behaviour of porous media, since Fillunger (1913) had already stated in his first study on the theory of water-filled porous media that the pore water pressure has no influence on the strength of the solid skeleton….His valuable work on the consolidation problem (Fillunger 1936) in 1936, which contains the basic ideas of porous media theory, shows that he had fully understood the "principle of effective stress"…."

Largely the Geotechnical community accepts that Terzaghi (1936) formulated the concept of effective stress for saturated soils. According to him the "total principal stress" consists of two components i.e. (a) "neutral stress" which acts on soil solid and water in all direction with equal intensity having no impacts on volume change, and (b) an excess over the neutral stress called "effective principal stress" that acts solely on the solid phase and is responsible for all measurable effects due to change of stress on soil. Mathematically,

$$\sigma' = \sigma - u_w \tag{1}$$

where σ' is the effective stress, σ is the total stress, and u_w is the pore water pressure.

It was not until recently (Andrade et al. 2022) that a direct measurement of Terzaghi's effective stress for saturated soils on a limiting case was demonstrated using a hybrid optical–mechanical method.

The concept of effective stress for unsaturated soils is relatively complicated. Two approaches exist in the literature, each having their own merit and shortcomings. These are, (a) considering a single effective stress combining net stress and matric suction (Bishop 1959), and (b) considering net stress and matric suction as independent stress state variables (Fredlund and Morgenstern 1977).

The formulation by Bishop (1959) is stated in Eq. 2.

$$\sigma' = \left(\sigma - u_a\right) + \chi\left(u_a - u_w\right) \tag{2}$$

where u_a is the pore air pressure, $u_a - u_w$ is the matric suction and χ is the effective stress parameter. For water saturated conditions, χ assumes the value of 1 reducing Eq. 2 (Bishop's Equation) to Eq. 1 (Terzaghi's Equation). For dry conditions, χ assumes the value of 0. For partial saturation, χ is a function of degree of saturation. A couple of critics to Bishop's formulation of effective stress includes its inability to explain collapse phenomenon in partially saturated soils during wetting (Jennings and Burland 1962) and lack of a unique relationship between χ and the degree of saturation (Khalili et al. 2004). To address this, Fredlund and Morgenstern (1977) suggested treating $\sigma - u_a$ and $u_a - u_w$ as two independent stress variables and then introducing independent set of material properties for each stress variable. One of the critics to this approach is its inability to account for hydraulic hysteresis on mechanical stress paths due to separation of mechanical stress from hydraulic stress (Nuth and Laloui 2008). Khalili et al. (2004) pointed out that combining a macroscopic $(\sigma - u_a)$ and a microscopic $(u_a - u_w)$ stress variable is not the usual approach in continuum mechanics.

An inherent assumption in the aforementioned two formulations for effective stress is that the suction is induced solely by capillarity. This is not entirely valid, especially at low moisture contents, where adsorption also contributes to suction and plays a role in soil water retention (Mishra et al. 2021). Zhang and Lu (2020) defined a unified effective stress equation (Eq. 3) considering both capillarity and adsorption.

$$\sigma'_{ij} = \left(\sigma_{ij} - u_a\delta_{ij}\right) - \sigma^s(w)\delta_{ij} = \left(\sigma_{ij} - u_a\delta_{ij}\right) - \left[\sigma^s{}_{ads}(w) + \sigma^s{}_{cap}(w)\right]\delta_{ij} \tag{3}$$

where σ'_{ij} is the effective stress tensor, δ_{ij} is the Kronecker delta, $\sigma^s(w)$ is the suction stress defined as the summation of components due to capillarity $(\sigma^s{}_{cap}(w))$ and adsorption $(\sigma^s{}_{ads}(w))$. σ, $\sigma^s{}_{cap}$ and $\sigma^s{}_{ads}$ are all reliant on gravimetric moisture content (w).

Salinity of the pore fluid in a soil system generates osmotic suction (Mishra et al. 2019). It has been demonstrated that osmotic suction affects engineering behaviour of clayey soils (Zhang et al. 2020). Rao and Thyagaraj (2007) suggested the following Eq. that incorporates effects of osmotic suction in total stress when inundating compacted clays with saline solutions.

$$\sigma = \left(\sigma - u_a\right) + \alpha_o\left(\pi_F - \pi_0\right) \tag{4}$$

where π_F and π_0 are final and initial osmotic suctions of pore fluid. α_o is a parameter that varies between 0 and 1.

Miller (1996) argued that osmotic suction (π) should be treated as an independent stress state variable, therefore, requiring three independent stress variables ($\sigma - u_a$, $u_a - u_w$, π) to discuss engineering behaviour of partially saturated soils with saline pore fluid.

The aforementioned equations for effective stress are for two/three phase idealisation of soil without considering presence of or effect of biological pathways. How microbial presence and interactions alter physico–chemical properties of soils have been discussed in details in the preceding section. Such interactions not only modify the volume of pore space but also load–deformation response of soils. This necessitates consideration of the presence and metabolic pathways of biological systems on effective stress of soils.

The presence of microorganisms alters overall gradation of the soil system since the size of microorganisms varies from silt to clay size particles (Willey et al. 2008). This leads to alteration in the pore size of the soil system by filling the voids (similar to mixing clay size particles in a coarse–grained soil system since many microbes and clay particles are of similar size). Microbes not only densify the soil mass, but their cell wall can also handle some amount of external mechanical stress (Mueller and Levin 2020) extending to the orders of MPa (Considine et al. 2008; Hazael et al. 2016). The quantity of stress that can be carried by the microbes depends on the number of microbes present, cell wall structure, compositions, plasticity, and rigidity (Garcia-Rubio et al. 2020). Therefore, a soil system "having" microbes (read as "considering the presence of microbes") and without will carry loads differently, with the generated effective stress and pore water pressure varying in each case. This is an area that is open for research, and it expected that fundamental experiments and numerical modelling will add value to the current state of understanding.

Traditionally, the three phased idealisation of soil considers it to be comprised of soil solids, air and pore liquid. However, the consideration of additional phases to emphasise the relative importance and distinct properties of the new phase in the soil system is not unconventional. For example, (a) salts are considered as the additional fourth phase for marine soils (Noorany 1984), (b) a further distinction in the water phase (i.e., free water and bound water) is made while discussing about dielectric properties of soil (Mishra 2020), (c) the contractile skin (read as "air–water interface") is considered as a fourth phase in the context of unsaturated soils (Fredlund and Rahardjo 1993), with the requirement that it is construed to be a part of the water phase from the perspective of mass–volume relationships, but an as independent phase while discussing stress state of the soil. Our proposition of using the fourth phase as the "living phase" refers to the presence and effect of microbes along with the biomediated pathways on the engineering response of the soil system. A generalised theory may require that in addition to the three phases (solid, liquid, air), several additional/new phases have to be considered together; e.g., for unsaturated marine soils (salts and contractile skin as two additional phases) or for unsaturated soils with biomediation (contractile skin and living phase as two additional phases). However, in the context of this manuscript, we stick to a four phased idealisation where the "living phase" is considered as the only additional phase to highlight the contribution of this additional phase in particular. In the context of this framework, the other phases may exist while describing the phenomenological response of the system, but are considered to be merged with their parent phases in the idealisation (e.g., salts and organics in the soils are in the solid phase, contractile skin as the air–water interface). In the sections that follow, we will discuss how the additional "living phase" contributes to strength–flow–deformation behaviour of soil, and thereby advocating in favour of its consideration while describing engineering behaviour of soils.

Microbes undergo several metabolic processes, increase their population, and alter their properties to sustain in a porous media (Willey et al. 2008). They secrete adhesive (exopolysaccharides) and have several appendages (flagella, pili) to sustain in the liquid solid interface (Dunne 2002). These adhesive viscous structures behave differently under different environmental stress to initiate and maintain a contact or affinity to the heterogeneous solid surface (Flemming and Wingender 2010; Persat et al. 2015). Furthermore, these adhesive compounds including exopolysaccharides, extracellular polymeric substances (EPS), exoproteins, and extracellular DNA (eDNA) encase the microbial cells to form a slimy aggregate called biofilms (Flemming et al. 2016). The composition and structure of biofilms vary drastically with type of microbes and environmental conditions that makes it challenging to quantify its response upon load application. Biofilm exhibit viscoelasticity, a time-dependent response upon application of external stress (Charlton et al. 2019). The quantifiable viscoelastic property can be correlated with the composition and structure of the biofilm (Persat et al. 2015; Peterson et al. 2015; Charlton et al. 2019). Peterson et al. (2015) have used spring and dashpot model to predict the viscoelastic behaviour of subjected to mechanical loads. Clearly, the above mechanisms alter the pore fluid properties with expected changes in the pore water pressure, soil–fluid interaction and effective stress in a soil mass. Again, we will stress here that fundamental experiments and numerical modelling are needed to understand these interactions better.

Inspired from the biofilms, synthetic biopolymers have been utilised to modify the engineering behaviour of soil system. These biopolymers can be plant based or microorganism or animal derived polymers (Fatehi et al. 2021). Though these biopolymers show adhesive and viscoelastic properties, the adhesion mechanism differs with the soil type (Chang et al. 2015; Mahamaya et al. 2021). In sand, the biopolymer coats the sand grains and forms a strong adhesive film which bridges the sand grains. Desaturation (evaporation of water) further increases the bonding by moving the grains close to each other (Fatehi et al. 2021; Chang et al. 2020). These coatings by the biopolymers increase the area of contact between the grains and reduce the void space having a direct bearing on the effective stress of the soil system. Studies have been conducted to measure the effect of external load on the biopolymer treated sand in terms of liquid limit, strength, erosion resistance, etc. (Mahamaya et al. 2021; Smitha and Sachan 2016; Judge et al. 2022). But not much work has been done to corelate the alteration in the pore fluid properties and area of contact with the effective stress and pore water pressure measurement. In clays, the adhesion mechanism of biopolymer occurs due to the surface charge of clays that varies with the type of clay mineral. The level of interaction of biopolymer and clay depends upon the interlayer bonding of clay, cation exchange capacity of clay, surface charge of both clay and biopolymer (Fatehi et al. 2021). In general, biopolymer treatment has a greater efficiency when treated for clay compared to sand (Chang et al. 2015) due to stronger interparticle connection.

Microbes undergo several metabolic pathways and induce various organic and inorganic substances around the cell wall. Biofilms or biopolymers are the organic substance generated. Similarly, the inorganic materials include precipitation of several kind of minerals known as biominerals. Till date, more than sixty biominerals are discovered which can be synthesised via various microbes (Dhami et al. 2013). Among various biominerals, microbially induced calcium carbonate (MICP) has gained immense importance in geotechnics for various application such as improving strength and stiffness, reducing conductivity and liquefaction potential, carbon sequestration, etc. (Dhami et al. 2013). In the MICP process, the calcium carbonate biomineral precipitates in the soil voids and links the soil particles by making an effective bridge which alters the engineering behaviour of the treated soil (Mujah et al. 2017). The precipitated biomineral increases the area of contact by linkage with potential effects on stress carrying capacity of the grains. However, the rate of influence is highly dependent on the amount of biomineral precipitated and relative size of soil pores and biomineral (Dhami et al. 2013; Mujah et al. 2019). Interestingly, the amount and relative size are also influenced by the number of treatments, concentration of biomass and chemicals present, and other environmental conditions. The influence on the pore water pressure of MICP treated soils also vary with the soil type and its condition (Montoya and Dejong 2015; Zamani and Montoya 2015, 2019). For instance, in MICP treated loose sand, excess negative pore pressure is generated, and dilative tendencies was observed like dense sand (Zamani and Montoya 2015, 2019). In sand with varying silt content, MICP treatment mostly decreases the excess negative pore water pressure generated (Zamani and Montoya 2015). However, the change in pore pressure mostly depends on the level of cementation (Montoya and Dejong 2015; Cui et al. 2017).

Microbial processes also produce different type of gases such as methane (CH_4), nitrogen (N_2), hydrogen sulphide (H_2S), and carbon dioxide (CO_2) in the natural soil, landfills, and other contaminated soil. Since most gases are soluble and not inert, either they get solubilised and cannot help in enhancing the mechanical properties of soil. But, the chemically inert and non-soluble nitrogen biogas has been applied for the mitigation of both static and earthquake induced liquefaction potential by desaturating the saturated sand (Peng et al. 2021; O'Donnell et al. 2017). The nitrogen gas is produced in biological nitrification process from nitrate and nitrite via denitrifying bacteria. The rate of gas generation depends on the nutrient availability, atmospheric condition, and type of sand, which further influences the rate of change in pore water pressure (Rebata-Landa and Santamarina 2012). Literature reveals that under static and dynamic loading, there is a decrease in the pore water pressure due to biogas production, that assists in mitigating liquefaction. However, generation of large amount of gas can provide an instability which needs to be accounted for by providing adequate amount of nutrient. Various theoretical and numerical model have been presented to measure the saturation, pore water pressure changes and mechanical response due to biogas production and its potential applications (O'Donnell et al. 2016; Hall et al. 2018; O'Donnell et al. 2019).

Considering the above discussion, and accounting for the fourth phase in a soil system that represents a living phase encompassing the biological agents, pathways and their effects on soil system, the following generalised equation for effective stress may be proposed.

$$\sigma' = \left(\sigma - u_a\right) + \chi\left(u_a - u_w\right) + \alpha_o\pi + \nu\Psi_{lm} \tag{5}$$

where Ψ_{lm} is the difference is the component of total stress that originates from biomediation. ν is a parameter varying between 0 and 1. ν assumes a value of 0 in an idealised case where there is no biological influence on the soil system and is a function of the volumetric living/bio mater content (θ_{lm}) as defined in the four-phase idealisation of the soil system (Mishra et. al. 2017a). The upper limit 1 is reserved for a condition where the soil system reaches a state where no further contributions to effective stress is expected irrespective of any further increase in the volume and influences from the biological considerations.

4.2 Strength and stiffness

Shear strength of soils (τ) is one of the key parameters routinely used in geotechnical design. There exist several constitutive relations to describe shear strength of soils of which Mohr Coulomb (MC) equation is the widely used one. It correlates the developed shear stress on a soil mass to the applied stress through two material properties i.e. cohesion (c) and angle of internal friction (ϕ) of the soil system. For saturated soils, MC equation is stated as

$$\tau = c' + \sigma' \tan \phi' = c' + \left(\sigma - u_w\right)\tan\phi' \tag{6}$$

Unsaturated behaviour of soil and consideration of osmotic suction in soil is often encountered through an extension of MC equation by modifying the component that deals with the stress variable and angle of internal friction. Two approaches exist; the first one considers a unitary effective stress variable (Bishop 1959) for unsaturated condition, while the second approach treats net stress and matric suction as two independent stress state variables (Fredlund et al. 1978).

$$\tau = \begin{cases} c' + \left[\left(\sigma - u_a\right) + \chi\left(u_a - u_w\right)\right]\tan\phi' & (\textit{unitary effective stress variable}) \\ c' + \left(\sigma - u_a\right)\tan\phi^a + \left(u_a - u_w\right)\tan\phi^b & (\textit{independent stress state variable}) \end{cases} \tag{7}$$

Following the work of Miller (1996) to treat osmotic suction as an independent stress state variable, Eq. 7 can be extended to Eq. 8 to encounter unsaturated soils with osmotic suctions.

$$\tau = c' + \left(\sigma - u_a\right)\tan\phi^a + \left(u_a - u_w\right)\tan\phi^b + \pi\tan\phi^c \tag{8}$$

where c' is the effective cohesion; ϕ', ϕ^a, ϕ^b and ϕ^c is the angle of internal friction with respect to changes in σ', $\sigma - u_a$, $u_a - u_w$ and π, respectively.

The friction and cohesion properties of soils are the basis to understand their shear strength. Friction between soil grains is generated due to their inherent surface roughness and adsorption on grain surfaces. Cohesion, on the other hand, refers to the adhesion irrespective of any externally allowed loads. It may stem from several possible mechanisms including cementation, interparticle attractive forces and adhesion (Mitchell and Soga 2005).

Many biogeochemical processes occur in nature that have an impact on the strength and stiffness of the soil system. The three most utilised biogeochemical processes for strengthening the soil mass are biomineralisation, biopolymer application and biogas generation.

4.2.1 Biomineralisation

The precipitated biomineral in the pores during biomineralisation makes an effective bridge between the soil grains that enhances the strength of the soil. MICP or enzyme induced carbonate precipitation (EICP) processes provide an apparent cohesion and increase the strength of geomaterial (Choi et al. 2020). Choi et al. (2020) proposed an empirical equation for estimating unconfined compressive strength (UCS) of various soil size and type treated via MICP linked with the amount of biomineral precipitated (ACP). Although, the proposed equation by them is fitted for most of the data with a strong coefficient of determination (0.81), the scattering suggests that the strength increment depends not only on the carbonate biomineral content but also on other factors such as size, morphology of precipitation and its bonding with soil grain (Rahman and Hora 2017; Xiao et al. 2019; Liu et al. 2019).

Shear strength measurements have shown an increase in the cohesion intercept, peak and residual frictional angle of the MICP/EICP modified soils (Montoya and Dejong 2015; Dejong et al. 2010; Cui et al. 2017). Most of the above studies have concluded that the behaviour of MICP treated soil is dependent upon the initial density and amount of biomineral precipitates. Also, the ductility also changes with the rate of cementation. The brittleness index (BI) (Consoli et al. 1998) showed a good correlation with amount of biomineral precipitated (ACP) (Rabbi et al. 2019).

Drained shear tests on MICP treated soil show an increase in the peak and residual strength and dilative behaviour with an increase in the ACP (Nafisi et al. 2019, 2020). Some studies have also attempted to understand the bond formation between the sand grains due to biomineral precipitation via DEM modelling (Khoubani et al. 2018; Feng et al. 2017). These models could capture peak and residual strength, nonlinearity, and softening behaviour due to MICP treatment of soil.

4.2.2 *Biopolymer application*

Application of biopolymers is widely used for improving strength of the soil system (Chang et al. 2016; Chen et al. 2016; Liu et al. 2018). Several studies have been conducted to study the impact of biopolymer on UCS, cohesion and friction of the soil system (Chen et al. 2016; Smitha and Sachan 2016; Fatehi et al. 2021; Choi et al. 2020). Shear behaviour of biopolymer treated soil showed a relatively large increase in cohesion intercept and minor increase in frictional angle (Chang et al. 2020). No chemical reaction occurs between the sand grains and biopolymer due to net zero charge on sand surface. Therefore, the enhancement in the shear strength is mostly dependent upon hydrogel formation, coating of sand surface, bridge formation and bond formation (Choi et al. 2020; Fatehi et al. 2021). During desaturation (evaporation of water), the dried biopolymer matrix shows increased cohesion by drawing sand grains closer to each other and hydrogel condensation (Chang and Cho 2019; Chang et al. 2018). However, for clays, the interaction is more complex since clay particles have unbalanced electrical charges on their surface. Various chemical bond such as hydrogen bonding, ionic bonds, van der Waals bonds are formed along with coating of surface by biopolymers (Mahamaya et al. 2021) in case of clays. These factors speak to an increased strength of the soil mass upon biopolymer application.

4.2.3 *Biogas generation*

Biogas formation can drastically influence the pore water pressure of sand. Martinez et al. (2003) demonstrated an increase in the undrained stiffness and drained strength in the soil injected with *Bacillius Subtilis* due to gas generation and change in saturation. Studies have also looked at the effect of biogas formation by denitrifying bacteria in mitigating the liquefaction by desaturation of sand (Rebata-Landa and Santamarina 2012).

Several other biologically mediated processes have also been utilised to remediate problematic soils which indirectly impact the strength and stiffness of soils (Panda et al. 2017; Levett et al. 2022). For example, Panda et al. (2017) tried to reduce the alkalinity of bauxite residue via various native and non-native microbes and found that the neutralized red mud has altered strength properties via formation of new mineral during bio-neutralisation.

Considering the above discussion and recognising the impact of biological processes on shear strength of soils, Eq. 8 can be further generalised in two ways to embed the biological influences i.e. either by treating Ψ_{lm} as an independent stress state variable or by capturing the influence through apparent cohesion (c^{lm}) attributed to biological pathways. Mathematically,

$$\tau = \begin{cases} c' + T + \Psi_{lm}\tan\phi^{lm} & (\textit{modification to frictional component}) \\ c^{lm} + c' + T & (\textit{modification to cohesional component}) \end{cases} \tag{9}$$

where $T = (\sigma - u_a)\tan\phi^a + (u_a - u_w)\tan\phi^b + \pi\tan\phi^c$, ϕ^{lm} is the angle of internal friction with respect to changes in Ψ_{lm}.

4.3 Volume change behaviour

Volume change behaviour of soils is an important consideration while evaluating their engineering properties (Mishra et al. 2020a, b). The following set of constitutive equations are applicable to link the applied stress on the soils to its volume change behaviour (Fredlund and Rahardjo 1993; Miller 1996; Mishra et al. 2019).

$$\partial e = \begin{cases} a_v \cdot \partial\left(\sigma - u_w\right) & (\textit{for saturated soils}) \\ a_t \cdot \partial\left(\sigma - u_a\right) + a_m \cdot \partial\left(u_a - u_w\right) & (\textit{for unsaturated soils}) \\ a_t \cdot \partial\left(\sigma - u_a\right) + a_m \cdot \partial\left(u_a - u_w\right) + a_\pi \cdot \pi & (\textit{for unsaturated soils with osmotic suction}) \end{cases} \quad (10)$$

where a_v, a_t, a_m and a_π are the coefficients of compressibility with respect to effective stress under saturated conditions, net normal stress, matric suction, and osmotic suction, respectively. ∂ operator is used to represent small changes in void ratio (e) or the respective stress variable ($\sigma - u_a$, $u_a - u_w$, π). It has been suggested that so long as the initial void ratio of the sample, boundary condition for loading remains the same, the shape of the deformation behaviour of sample represented by change in void ratio vs. change in applied stress plots for sample in semi logarithmic scale is independent of the mode of stress application be it purely hydraulic or mechanical stress (Baumgartl and Köck 2004; Mishra et al. 2021).

Though, the geotechnical engineers assume the compressibility and volume change behaviour mostly depend on the soil properties and load condition, the microbes present, and their microbial activities can drastically alter the volume of a soil system.

Microbes are widely linked in the adsorption, fixation, decomposition, dissolution, transformation of different soil minerals in nature (Mitchell and Santamarina 2005; Li et al. 2019; Fomina and Skorochod 2020). This degradation and transformation process could alter the void structure drastically which has a direct impact on the compressibility behaviour. A heave of 480 mm was observed on mudstone sediments in Iwaki-City of Japan linked to various microbial activities (Mitchell and Santamarina 2005). After several laboratory experiments, it was concluded that a series of microbial activities i.e., sulphate reduction, sulphate oxidation, pyrite oxidation resulted in the formation of gypsum and jarosite crystals which attributed to the heave (Yamanaka et al. 2002).

Biomineralisation impacts the compressibility behaviour of soils. For MICP treated silica sand of different grain size and cementation levels particle breakage could be restricted by making new bridges between soil grains; this resulted in decrease in the compressibility (Xiao et al. 2021; Ghasemi et al. 2022). The compression test results showed negligible reduction in the void ratio at low vertical stress range in the MICP treated sand due to the formation of effective bridge or bonding during biocementation (Wang et al. 2022). However, MICP treated sand behaves like untreated sand at high stresses. Cementation content, vertical stress and relative density of sand are the factors having an impact on the breakage of interparticle bonding and altering the compressibility behaviour of soil (Wang et al. 2022). The damage of interparticle bonding can be three types i.e. debonding, abrasion and detaching. MICP treatment has shown similar modification in the compressibility behaviour when applied on fine-grained soils (Canakci et al. 2015; Montoya et al. 2019). Literature shows that MICP treated soils have two consolidation yield stresses. The reduction in void ratio is negligible up to a particular stress i.e., first consolidation yield point. Beyond this point the interparticle bond starts breaking and the biomineral starts taking up the stress applied with a slow reduction in the void ratio or deformation until the second consolidation yield stress. Afterwards, the compression curve converges with that of the untreated soil. To understand this behaviour, a schematic diagram is presented in the Fig. 5 with the results shown adapted from that reported by Xiao et al. 2021. The three graphs shown in Fig. 5 refers to sand with a coefficient of uniformity of 1.1, either untreated (SU-C1.1) or treated with different dosages for MICP (ST-C1.1-Ca1, ST-C1.1-Ca2). The coefficient of volume compressibility and compression index is less for the biomodified sample up to secondary yield stress point and after that the corresponding values are nearly equal to those of the untreated samples (Canakci et al. 2015; Montoya et al. 2019). Although biotreatment reduces the primary consolidation, the time for consolidation increases due to the reduction in permeability. In this context, since the initial testing conditions vary, principle of critical state soil mechanics (CSM) may be considered to interpret the experimental results. CSM principles dictate that the slope of the post yield

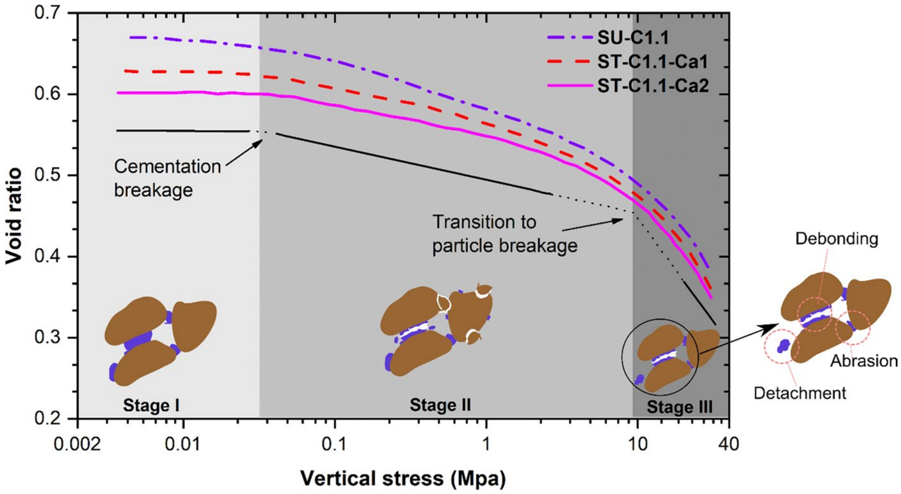

Fig. 5 Load deformation behaviour of MICP treated and untreated soils (modified from Xiao et al. 2021)

compression line is unique and independent of initial state of soil.

Xanthan gum and guar gum have been used to stabilise various types of soils modifying their compressibility behaviour (Singh and Das 2020; Kumar et al. 2021; Sujatha and Saisree 2019). The mechanisms for biopolymer interaction varies hugely with the type of soil and biopolymer, rheological properties of biopolymer, and surface properties of the soil and polymer as described by Fatehi et al. (2021) and summarised in Fig. 7. Due to the large variation in the interaction, different biopolymers act differently in geomaterials while altering their compressibility behaviour. For example, though Xanthan gum is used to stabilise highly plastic silts, the soft compressibility nature of Xanthan gum linkage increased the compression index of soil (Singh and Das 2020). Similarly, the Coefficient of consolidation and compression index increased during the addition of guar gum in the sand–clay mixtures (Kumar et al. 2021). Contrary to this observation, the study by Sujatha and Saisree (2019) concluded that the highly viscous guar gum forms strong hydrogels between soil grains and helps to reduce the compression index, compressibility of highly compressible silt–clay mixtures. High percentage of biopolymer content also reduces the volumetric change during wet–dry cycles on biopolymer treated soil. The studies show that natural or human injected biopolymer have significant effect on the compressibility behaviour of soil. However, the studies need further comprehensive analysis pertaining to the soil initial condition, type of interaction and its effect on compressibility and volume change. Also, limited studies have been conducted on the effect of type and concentration of biopolymer, condition of loading and unloading, wetting–drying path on the compressibility behaviour of biopolymer treated soil.

Considering the biological mediation and defining the biological coefficient of compressibility (a_{lm}), the generalised constitutive equation describing volume change behaviour of soils under applied load can be formulated as the following.

$$\partial e = a_t \bullet \partial\left(\sigma - u_a\right) + a_m \bullet \partial\left(u_a - u_w\right) + a_\pi \bullet \pi + a_{lm} \bullet \Psi_{lm} \tag{11}$$

The biological processes alter the pore structure and contacts between soil grains which impact on the geotechnical behaviour such as strength, stiffness, and volume change behaviour of soil. The alteration in microstructure of soil system during various loading is efficiently analysed by different constitutive models (Chiu and Ng 2003; Monroy et al. 2010; Vecchia, and Romero 2013; Alonso et al. 2013). Biomediated processes such as behaviour of MICP-modified soil is also explained by various constitutive models (Feng et al. 2017; Gai and Sánchez 2019; Lu et al. 2021; Wang et al. 2023; Ahenkorah et al. 2023). These studies suggest that the models can efficiently predict the mechanical behaviour of soil modified with MICP. However, further fundamental studies and unified coupled modelling of biological processes, the alteration in pore space, and linkage in soil grains due to biological processes needs to be carried out for implementing the significance of microbial processes in geotechnical design.

4.4 Conduction phenomena

Soils are multiphasic porous materials, in which different degrees of physical connection exist between the individual phases. This allows traversal of fluids (liquids and gas), electricity, heat, and contaminants through them under applied fields that induce a differential of the respective quantities across the soil system. The differential potentials are hydraulic head for water flow, voltage for electrical flow, temperature difference for thermal migration or a chemical gradient for contaminant transport. The constitutive equation linking rate of flow (J) to the driving force (F) is a linear equation involving a material (soil) specific parameter (ζ) describing the ease with which the respective flow can occur through the soil mass (Mitchell 1991). Mathematically,

$$J = \zeta F \tag{12}$$

Equation 12 takes various forms depending on the type of flow under consideration (Eq. 13).

$$\begin{aligned} q_h &= k_h i_h A \quad (\textit{Water flow} - \textit{Darcy's law}) \\ q_t &= k_t i_t A \quad (\textit{Heat flow} - \textit{Fourier's law}) \\ q_e &= k_e i_e A \quad (\textit{Electrical flow} - \textit{Ohm's law}) \\ q_c &= k_c i_c A \quad (\textit{Chemical flow} - \textit{Fick's law}) \end{aligned} \tag{13}$$

where q_h, q_t, q_e and q_c represent the hydraulic, thermal, electrical and chemical flux through the soil mass, respectively. i_h, i_t, i_e and i_c represent the hydraulic, thermal, electrical and chemical gradient across the soil mass, respectively. k_h, k_t, k_e and k_c represent the hydraulic, thermal, electrical and chemical conductivity of soil mass, respectively. A represents the cross-sectional area of the soil. A comprehensive treatment of each of the conduction phenomena and their coupling has been presented elsewhere (Mitchell 1991; Mitchell and Soga 2005).

4.4.1 Flow of heat

Three mechanisms govern thermal migration through soils. These mechanisms are conduction (heat transfer through particular contact), convection (heat transfer through pore fluids) and radiation (heat transfer through electromagnetic waves, of which conduction remains as the predominant mode of heat transfer through soils. For partially saturated soils, the factors that affect thermal conductivity include mineralogy, dry density, gradation, moulding moisture content and time (Brandon and Mitchell 1989). There exists number of models (Kersten 1949; de Vries 1963; McGaw 1969; Johansen 1975; Farouki 1982; Mishra et al. 2017a, b) that predict thermal conductivity of soils based on known geotechnical properties.

Several laboratory experiments demonstrated that, MICP treatment enhances the thermal conductivities of soil by significant factors (Venuleo et al. 2016; Martinez et al. 2019; Wang et al. 2020; Xiao et al. 2021b). The increase in thermal conductivity was attributed to the precipitation of calcite crystals increasing the contact area and act as a thermal bridge between the soil grains (Ref. Fig. 6). The rate of enhancement in the thermal conductivity of MICP modified soil differs with number of treatment cycles, degrees of saturation and soil conditions (Martinez et al. 2019; Xiao et al. 2021b). Martinez et al. (2019) proposed that measurement of thermal properties may provide a proxy for assessing cementation levels and contact quality during MICP treatment.

Not only MICP, several other biochemical reactions also can have a significant impact on the thermal conduction phenomenon. For instance, Mishra et al. (2017a) observed short term increase in thermal conductivity of sand bentonite mixtures, fly ash, red mud and a local dispersive soil from India treated with an extremophile gram positive bacterium. They proposed that the observed increase in thermal conductivity may be linked to phasal augmentation or some form of biogeochemical reaction, which was explained through a four phased idealisation of the soil system. Several artificial intelligence-based algorithms were used by the authors to develop pedotransfer functions for thermal conductivity of the materials based on the experimental data.

It, therefore, is evident that biological treatments do alter thermal conductivity of soils. Such alterations are attributed to the changes in the level of densification, mineralogy and particular contact that hold a direct bearing with thermal migration through soils through heat conduction.

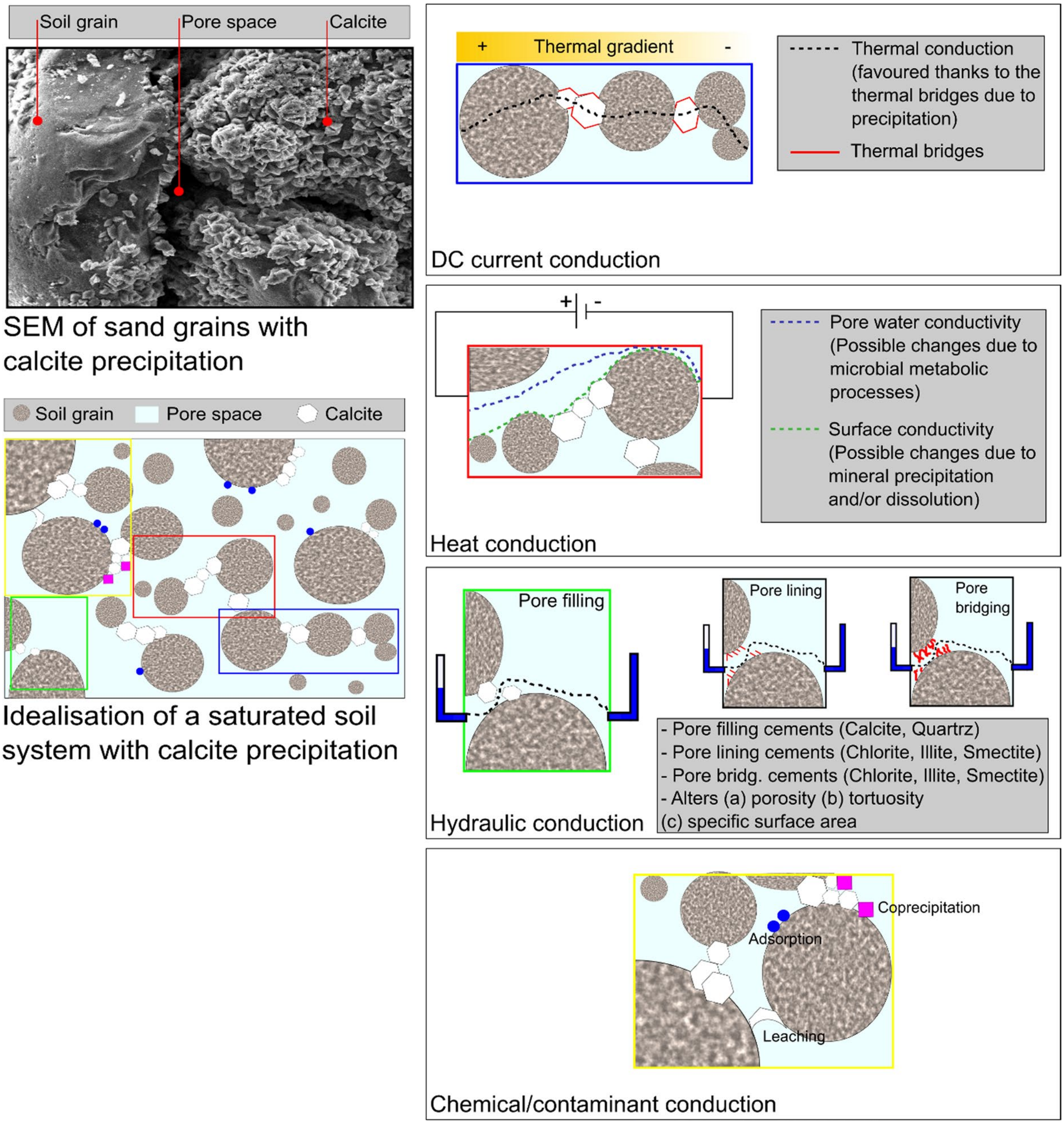

Fig. 6 Mechanisms of conduction of heat, electric current, water, chemicals in MICP treated soil

4.4.2 *Flow of electrical current*

A thorough treatment on the impacts of biological considerations on electromagnetic (EM) properties of soils have been presented in the second review paper focused on potential usage of EM methods as a monitoring tool to capture biological interactions. In this part, we will limit our discussion to some of the reported applications.

Al Hagrey et al. (2004) used electrical measurements to quantify the flow of water through soil–plant–atmosphere continuum. They used geoelectric, ground penetrating radar (GPR), time domain reflectometry (TDR) methods and suggested that soil water, structure, penetration of root zones and water uptake by them can be monitored using electrical measurements.

Furman et al. (2013) described that electrical resistivity tomography (ERT) may be used as the simplest and cheapest non-destructive tool to map and monitor the processes around the root zone. However, they also noted that the method works well for subsurface that is relatively homogenous and for measurements over a relatively large scale.

Masy et al. (2016) ERT to monitor biodegradation of petroleum hydrocarbons in Rhine sand using a gram-positive biocatalyst. In this case, time lapse ERT measurements could furnish electrical resistivity signatures correlating well with the progress of bioremediation.

Mishra et al. (2017c) observed an increase in electrical conductivities of sand bentonite mixtures, fly ash, red mud and a local dispersive soil from India treated with an extremophile gram positive bacterium. The direct current (DC) conductivity was obtained using an electrical conductivity probe embedded in the soil, where a DC voltage was applied across the two intermediate electrodes and the DC current was measured across the two extreme electrodes. It was noted that DC electrical conductivity increased with an increase in the degree of saturation, volumetric moisture content and percentage of the bacterial addition.

Sani et al. (2020) used a native soil bacterium to treat a lateritic soil using MICP technique and conducted DC resistivity testing. They noted an increase in electrical resistivity with an increase in suspension density of the bacterial solution, compactive effort and the no. of curing days (upto 28 days).

Sun et al. (2021) used a LCR meter to measure DC resistivity (inverse of conductivity) of Yangtze river sand (China) solidified using MICP technique. They noted a linear relationship between UCS, porosity and electrical resistivity of the MICP treated sand. However, electrical resistivity of the samples correlated inversely with their carbonate content.

DC resistivity/conductivity of soils is often approximated as two resistors in parallel each representing resistance/conductance of the pore fluid and that of the surface (Ref. Fig. 6), respectively (Waxman and Smits 1968). During biomineralization, changes in DC resistivity/conductivity is linked to changes in the electrical conductivity of the pore fluid (due to microbial metabolic processes), changes in the pore structure and changes in the electrical properties of the mineral constituents (due to precipitation and dissolution of minerals) (Aetkwana and Slater 2009). Because of the existence of several compounding factors during biomineralization that can alter the DC resistivity/conductivity, the applicability of DC resistivity method during biomineralization is restricted (Ntarlagiannis et al. 2022).

To summarise, the alterations in soil properties due to biological activities leads to changes in the electrical properties of soil. Therefore, electrical methods can be used to measure and monitor biomediated and bioinspired soil processes.

4.4.3 Flow of water

Flow of water through soils is governed by the existing hydraulic head differential, and its rate is described with a quantity named as hydraulic conductivity. The major factors that influence the water flow through soils include porosity, tortuosity, specific surface area (SSA) of the grains and the properties of the pore fluid. The presence of biological systems and their interactions with soil affects the soil-pore properties and surface and pore properties of the soil system, thereby influencing the flow of water through soil.

Bacterial adhesion and deadhesion in a soil system with flow of water is affected by relative size of pore to a single microbe or microbial colony, microbial shape, roughness of grains, surface charge of both microbes and grains. Among all the factors, the pore size of soil is one of the major influencers for the bacterial adhesion Hazen's effective diameter (D_{10}) is used as a proxy to estimate the soil particle range that can be affected by the bacterial retardation, biofilm formation and bioclogging (Mitchell and Santamarina 2005). An example of natural bioclogging phenomenon is the oxidation pf pyrite precipitates gypsum and iron hydroxide which clogged the drainage blanket resulted in the stability failure of Carsington Dam in 1984 by the autotrophic bacteria (Mitchell and Santamarina 2005).

The precipitated biominerals during MICP in the pores clog the voids and increase the tortuosity resulting in an increase in the resistance to flow (Mujah et al. 2017). Several studies shown that the reduction in permeability is mainly dependent on the amount of biomineral precipitation (Qabany and Soga 2013; Whiffin et al. 2007; Gao et al. 2019). However, the amount of precipitation varies with the environmental condition, type and concentration of microbes and chemical reagents (Zhao et al. 2014; Ng et al. 2012; Jain and Arnepalli 2019a, b). It is observed that 2% of biomineral precipitation is effective in controlling seepage and 50–90% of reduction in permeability is possible with 10–15% precipitation (Whiffin et al. 2007; Gao et al. 2019; Yasuhara et al. 2011; Qabany and Soga 2013). Several researchers have derived empirical equations to calculate the permeability of MICP treated soil by corelating it with the amount of biomineral precipitated (Gao et al. 2019; Choi et al. 2020). Mineral cementation of sands alters the porosity, tortuosity and SSA through 3 fundamental mechanisms (Neasham 1977; Panda and Lake 1995; Lin et al. 2020). These three mechanisms (Ref. Fig. 6) include (a) pore filling (in case of calcite, quartz and feldspar), (b) pore lining (in case of chlorite, illite and smectite), and (c) pore bridging (in case of chlorite, illite, and smectite).

Biofilms and biopolymers also contribute to reduction in hydraulic conductivity (Dunsmore et al. 2004; Chang et al. 2016; Tiwari et al. 2016; Chang et al. 2020; Fatehi et al. 2021). The three major sources for deriving the biopolymers include polynucleotides, polypeptides, and polysaccharides (Chang et al. 2020; Fatehi et al. 2021). Most polysaccharide-based biopolymers have hydrophilic behaviour and form a viscous hydrogel in the presence of water. The rheology or viscous nature mainly depend on the type of biopolymer and water content ratio (Choi et al. 2020). Therefore, the change in the biopolymer modified soil system is mostly regulated by the rheology of biopolymer and the bonding formation between biopolymers and soil grains. The type of bond formation between the biopolymer and soil particles depends on the type of soil and biopolymer used. In sandy soil, biopolymer solution soaks the electrically neutral silica-based particle and coats the sand surface. After coating, it aids formation of bridges between the grains (Fatehi et al. 2021). Upon drying, the bond strength increases as the particles are drawn close to each other. The coating and bridge formation can be modelled same as pore filling and pore bridging mechanism of MICP treated soil. The interaction of biopolymer in a clayey system is more complex due to presence of surface charges on clays. 1:1 clays (e.g. kaolinite) absorbs less biopolymers since the interlayer is bonded with hydrogen bond. 2:1 clays (e.g. montmorillonite) can absorb higher biopolymer solutions as the constituting sheets are joined with weak Van der Waals force. Figure 7 presents a schematic of interaction of biopolymer with sand gains and clay particles.

To summarise, biomediation affects porosity, tortuosity, SSA and the properties of the pore fluid of the soil system which has a direct bearing on flow of water through it.

4.4.4 *Flow of chemicals/contaminants*

Transport of chemical species in sandy soils is controlled by advection, where the species is accompanied with the water flow. During the microbial treatment in soils, the microbes can flow due to passive

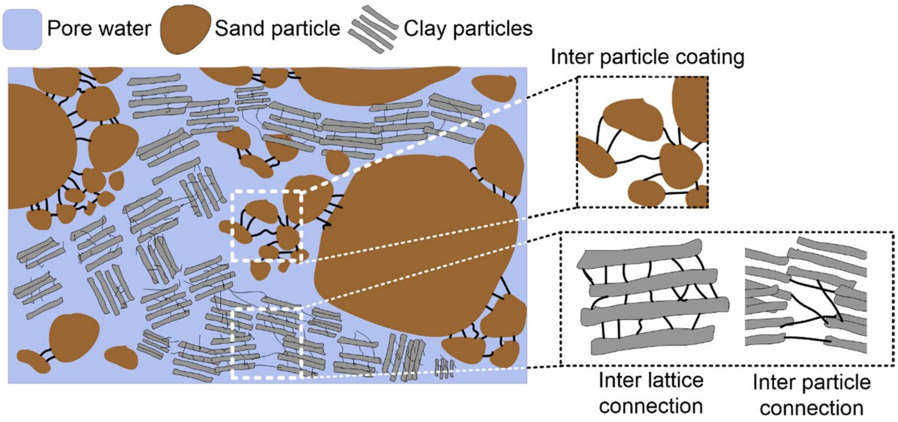

Fig. 7 Interaction mechanism of soil and biopolymers

diffusion and their transport in the porous media is well studied (Murphy and Ginn 2000). For homogeneous immobilisation or fixation of microbes in the sand surface, adhesion and deadhesion of microbes have been studied and calculated by DLVO theory under variable pore fluid chemistry (Harkes et al. 2010; Jain et al. 2021). The biotreatment in sand alters its permeability and could reach to a very small range for horizontal permeability comparable to fine grained soils where chemical diffusion plays an important role.

Fick's law is the governing relationship, and the diffusion coefficient is the controlling parameter during chemical transport in the soil system. The flow is mostly dependent upon the chemical concentration gradient in aqueous flow condition. In a soil system, the diffusion of a chemical species is more complex due to (a) cross-sectional area reduction, (b) tortuous flow, (c) effect of electrical force of soil grain, (d) retardation of species due to ion exchange, adsorption, precipitation (e) biodegradation of diffusing organics, (f) osmotic counter flow, and (g) electrical imbalance (Mitchell and Soga 2005).

Microbes and biofilms present in a soil system adsorb various chemical species due to their negatively charged cell wall and charged biofilm. Microbes also degrade various compounds via their metabolic activities resulting in a change in the diffusion coefficient. Biosorption and biodegradation are well-studied in the field of bioremediation (Ren et al. 2018; Punetha et al. 2022; Varghese et al. 2021). Furthermore, microbes are well known for the solubilizing of low-grade ores or minerals such as copper, uranium, gold and assist in the bioleaching process (Bosecker 1997). Bioleaching alters the diffusion coefficient.

During MICP treatment of soils, if there is flow of chemical species due to chemical potential gradient, the diffusion coefficient is altered by the coprecipitation of heavy metals. Various studies have been conducted to precipitate and/or coprecipitate heavy metals and radionuclides in the soil system via MICP (Kang et al. 2016; Achal et al. 2012; Jain and Arnepalli 2019a, b; Kumari et al. 2014). In MICP treated soils, the surface charge also alters due to pore coating of soil grains which affects the diffusion behaviour. During biopolymer treatment in the soil, the diffusion of chemical species can vary by (a) altering the charge of the soil system due to coating and aggregation of soil surface, and (b) adsorption of various species. Several studies have been conducted to utilise natural biopolymer as an absorbent for heavy metals and other organic and inorganic pollutant (Efimova et al. 2017; Barrida et al. 2008; Mondal et al. 2022). Recently, Kumar et al. (2021) demonstrated that a 2% guar gum treatment in sand–clay mixture was effective in adsorbing heavy metals and as showed potential for usage in liner systems. However, these studies did not consider the diffusion coefficient and flow of chemical species during biopolymer treatment of soil.

In summary, biological pathways alter chemical transport through soils through 3 mechanisms including (a) aiding in adsorption of chemical species, (b) precipitation and co-precipitation of minerals and (c) leaching of minerals from the soil system. These three mechanisms have been highlighted in Fig. 6.

4.5 Durability

Assessing the long-term effect of biomediated soil processes on geotechnical design is crucial. Microbes are living organisms hence the effect of the microbes on soil systems may not be permanent. However, mediation by the microbes can alter the physical nature of geomaterial, permanently. Moreover, a single microbial cell may act as a nucleus and accelerate mineral formation. Hence, the physical changes due to microbial mediation needs an in-depth study in the future for quantifying the durability effect.

Though the presence of microbes is not permanent, the production of different metabolic products such as various organic and inorganic substances generated from the microbial processes, has a prominent long-term effect on the geomaterial.

Microbes segregate biofilms to attach to the mineral surface and signal transformation. These biofilms are long carbon chains having different compositions and surface charges. These biofilms or other plant-derived biopolymer are being used in enhancing the soil behaviour due to their high viscosity and hydrogel formation. These hydrogels either link or aggregates the soil grains and/or coat the soil surface as shown in Fig. 8. However, these polymers are mostly organic and decompose naturally with time (Mahamaya et al. 2021). The degradation process decomposes the hydrogel formation in the soil pores and weakens the soil grain linkage which impacts the overall strength and stiffness of the soil (Sujatha and Saisree 2019; Mahamaya et al. 2021). The rate of degradation varies with the polymer composition, soil polymer interaction, and environmental conditions. In this regard, various studies have been conducted on the durability of biopolymer-stabilized soil. The general conclusion is that higher biopolymer content is more resistant to alternate wetting and drying cycles and it is advisable to use tested non-biodegradable or durable biopolymers (Soroudi and Jakubowicz 2013; Sujatha and Saisree 2019; Chang et al. 2020).

Figure 8 depicts the SEM image MICP-modified sand in which the carbonate biomineral can be seen coating the sand grains. Various studies have been conducted to assess the durability of MICP-treated soil and or concrete under different harsh conditions such as dry–wet cycles, freeze–thaw cycles, presence of marine or seawater, the flow of different contaminants, the effect of different pH solutions, etc. (Gowthaman et al. 2021; Huang et al. 2022; Li et al. 2023). The above literatures discuss the rate of weakening of the linkage and loosening of the strength is reliant on the extreme soil/environmental conditions. The studies also provide different solutions such as reinforcement with fibres, retreatment in intervals for the usage of MICP treatment in the field (Spencer et al. 2020; Shan et al. 2022).

5 Summary

This article summarises the theoretical advances that have been made considering biological inspiration and mediation in the discipline of soil mechanics and geotechnical engineering.

Biological inspiration provides efficient and feasible solutions to design infrastructure and non-destructive monitoring methods. Bioinspired data analysis offers the benefits to model and optimise the complex behaviour of soils and geotechnical systems. Therefore, at least in theory, it is possible to consider bioinspiration in the complete life cycle of a geotechnical system involving its design, monitoring and analysis of the monitoring data. In general, while bioinspired data analysis has reached technological maturity, bioinspired geotechnical infrastructure and monitoring are still in incipient phases of research and would need further fundamental advances before they can be applied in practice.

The manuscript further delivers the influence of microbes and their metabolic activities on the fundamental properties of geomaterials. These alteration in the fundamental properties bear consequences for the engineering behaviour of the soil system. To that end, in this study, the changes in engineering properties of soil considering biological mechanisms such as biofilm formation, biomineralisation, and biopolymer treatment has been critically reviewed. The review underpins the necessity of considering a four-phase idealisation of soil system by considering the biological presence and intervention as the fourth phase. This requires a shift in considering geotechnical engineering challenges from a "soil physics" perspective to an interdisciplinary "soil physics–soil chemistry–soil biology" based approach.

After having discussed the theoretical considerations to include biological inspiration and pathways in Geotechnical Engineering, in the second part of the

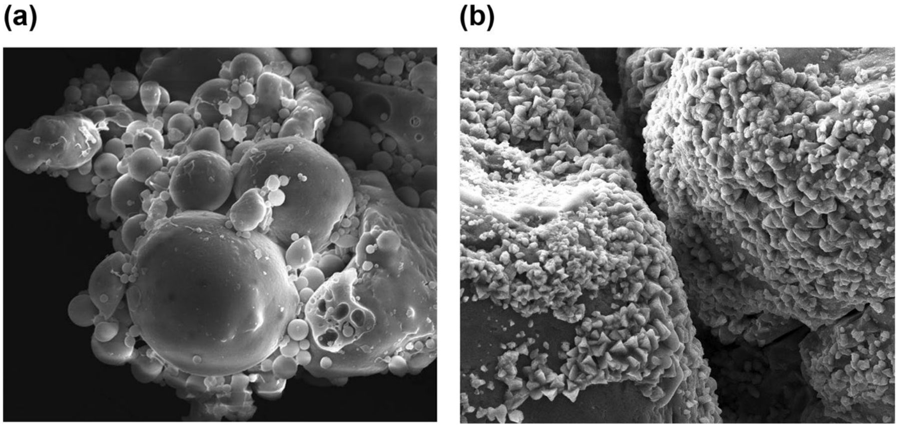

Fig. 8 **a** aggregation of fly ash particles after treatment with 1% of guar gum (after Mahamaya et al. 2021), **b** coating of sand grains with carbonates formed from MICP

review our attention will be on some of the practical considerations, case studies and monitoring methods.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Human and animal rights The study does not involve human participants and/or animals.

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