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CHAPTER 1

INTRODUCTION

1.1 General

The examination of fluid movement through porous media underpins the comprehension of various natural and engineering phenomena, including groundwater flow, soil drainage, waste disposal, and filtering. A porous media has a solid matrix with interconnected spaces or pores that facilitate fluid movement under pressure or gravity forces. The fluid movement in these materials is often regulated by Darcy's law, which establishes a correlation between flow rate and hydraulic gradient for a specific permeability. In practical systems, the architecture of porous media is seldom homogeneous. Natural formations such as soils, aquifers, and rocks exhibit intricate pore configurations arising from geological, chemical, or biological processes. Likewise, engineered porous materials, such as filters, concrete, or packed columns, demonstrate heterogeneity attributable to production techniques or material composition. This spatial variety, termed heterogeneity, is pivotal in influencing the movement of fluids and solutes within the medium. Heterogeneity influences factors like permeability, porosity, and tortuosity, resulting in favoured flow pathways, uneven pressure distribution, and erratic transport behavior. Minor alterations in pore dimensions or configuration can result in substantial modifications in flow velocity and direction. Identifying and measuring these changes is crucial for creating precise models that can forecast subsurface flow dynamics under varying hydraulic conditions.

In addition to groundwater and environmental applications, the study of fluid flow through heterogeneous porous media has considerable importance in geotechnical and petroleum engineering. In geotechnical systems, spatial variations in permeability strongly influence seepage through foundations and embankments, pore-water pressure development, consolidation behaviour, slope stability, drainage performance, and contaminant migration through soil and rock formations. Proper characterization of hydraulic conductivity is therefore essential for the safe design of foundations, earth dams, retaining structures, landfills, and other subsurface engineering works. Similarly, in petroleum reservoirs, oil and gas migrate through interconnected pore networks within

heterogeneous and often stratified rock formations. Variations in permeability, porosity, pore connectivity, fractures, and layer orientation can significantly affect hydrocarbon mobility, pressure distribution, displacement efficiency, and the overall recovery of oil and gas. Understanding such heterogeneity is therefore essential for predicting preferential flow paths, evaluating reservoir performance, and improving fluid extraction and injection strategies. These diverse applications demonstrate that a reliable understanding of flow behaviour in heterogeneous porous media is important not only in civil and environmental engineering but also in energy-resource and subsurface engineering systems.

9

1.2 Flow in porous media

A porous media is a material that contains voids or pores. The skeleton component of the material is frequently referred to as the "matrix" or "framework." The pores are generally occupied by a fluid (liquid or gas). The skeleton material is typically solid; however, structures such as foams can also be effectively studied utilizing porous media. A porous medium is primarily defined by its porosity. The medium's other properties (e.g., permeability, tensile strength, electrical conductivity, tortuosity) can occasionally be inferred from the qualities of its constituents (solid matrix and fluid), as well as the media's porosity and pore structure; however, this derivation is typically intricate. The notion of porosity is only clear in the context of a poroelastic medium. The solid matrix and the pore network, or pore space, frequently coexist as two interpenetrating continua, exemplified by a sponge. Numerous natural substances, including rocks and soil (e.g., aquifers, petroleum reservoirs), zeolites, biological tissues (e.g., bones, wood, cork), as well as synthetic materials like cement and ceramics, can be classified as porous media. Numerous fundamental features may only be elucidated by regarding them as porous media.

The concept of porous media is utilized in various domains of applied science and engineering, including filtration, mechanics (acoustics, geomechanics, soil mechanics, rock mechanics), engineering (petroleum engineering, bioremediation, construction engineering), geosciences (hydrogeology, petroleum geology, geophysics), biology, biophysics, and materials science. The movement of fluids through porous media is a widely recognized topic and has developed into an independent area of research. The examination of the overarching behavior of porous media, which includes the

deformation of the solid framework, is referred to as poromechanics. Various factors affect fluid flow in porous media, with its primary role being to spend energy and generate fluid through the wellbore. The relationship between energy and flow rate is the paramount concern in flow mechanics via porous media. Darcy's law is the principal law that defines this relationship.

1.3 Hydraulic conductivity

Hydraulic conductivity, or permeability, is the inherent property of soil that facilitates the passage of water through the interconnected gaps within the soil matrix. This flow occurs from a region of high to a region of low. Soil is classified as highly porous when it contains a significant volume of voids within its structure; it is deemed highly permeable if these gaps are interconnected, allowing for the effortless passage of water, as observed in gravel and coarse sand. Conversely, in less permeable soil, the pore spaces are separated, trapping water inside them and impeding its movement, resulting in low permeability, as observed in clay. Hydraulic conductivity in heterogeneous porous media varies spatially because the medium contains differences in soil composition, pore structure, particle arrangement, and stratification. These variations influence the continuity and resistance of flow paths, causing water to move more easily through highly permeable zones while being restricted by less permeable regions. In layered soils, the overall hydraulic conductivity depends on the properties, thickness, sequence, and orientation of individual layers. As a result, horizontal and vertical hydraulic conductivity may differ considerably. Understanding this variability is important for accurately evaluating seepage, groundwater movement, drainage behaviour, and contaminant transport in natural and engineered porous systems.

1.4 Engineering applications

Numerous issues in soil mechanics and hydraulic structures are directly associated with the physical attribute of soil permeability. The design of earthen dams, roadways, airports, and the output of water or oil from a well is pertinent to permeability. The characteristic of permeability ranges from very porous gravels to the most rigid clays. Gravels exhibit the maximum permeability, whilst clays demonstrate the lowest. The absence of sufficient understanding of soil permeability may result in significant issues in the design of earthen dams. Water infiltration through the embankment poses a risk to the dam's integrity, while seepage from the reservoir's sides and bottom results in

significant water loss. Consequently, the choice of location for such large-scale projects is determined by the soil permeability of the region. The placement of recharge wells for groundwater replenishment is contingent upon the permeability properties of the subsurface soil.

The assessment of permeability is crucial in the subsequent engineering challenges:

1.4.1 Seepage through earthen dams and canals

The assessment of permeability is crucial for evaluating seepage in earthen dams and canals, as it directly affects the safety, stability, and efficiency of hydraulic systems. In earthen dams, permeability dictates the velocity and distribution of water flow through the embankment and its foundation (Figure 1.1). Precise assessment of this feature enables engineers to devise efficient drainage systems, impermeable cores, and upstream blankets to reduce seepage losses and avert piping or internal erosion that could result in dam failure. In canals, the permeability of the bed and side slopes influences seepage losses, which can markedly diminish conveyance efficiency and lead to detrimental waterlogging or salinity in neighboring agricultural areas. Laboratory and field assessments, including falling head, constant head, and pumping experiments, are employed to ascertain permeability values across diverse soil conditions. Engineers use appropriate lining materials or compaction techniques to mitigate seepage and enhance water saving based on these results. The numerical modeling of seepage flow through Darcy's law and finite element methods aids in visualizing flow patterns and forecasting essential hydraulic gradients. The assessment of permeability is not solely a laboratory task but a critical engineering application that guarantees the structural integrity, economic efficiency, and sustainability of earthen dams and irrigation canal systems.

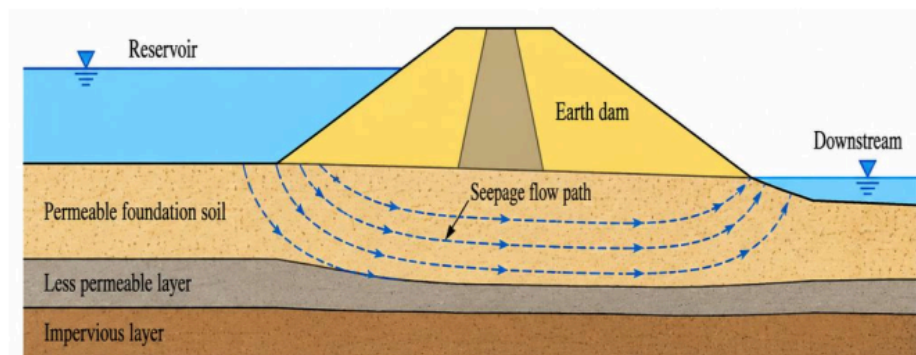


Figure 1.1 Seepage through foundation of earth dam

1.4.2 Uplift pressure under hydraulic structure

The assessment of permeability is essential for estimating uplift pressure beneath hydraulic structures, including weirs, barrages, and dams. Uplift pressure occurs when water infiltrates the foundational soil beneath these structures, generating an upward force that may jeopardize structural integrity if not adequately addressed (Figure 1.2). The intensity and distribution of uplift pressure are predominantly influenced by the permeability properties of the foundational material. The precise assessment of permeability by laboratory and field testing, including constant head, falling head, or pumping tests, allows engineers to determine seepage flow, hydraulic gradients, and pore water pressures beneath the structure. These criteria are crucial for the design of appropriate seepage control devices, including cutoffs, sheet piles, impermeable aprons, and drainage filters, which mitigate uplift pressure and enhance safety against floating and sliding. Soils with high permeability facilitate excessive seepage, resulting in heightened uplift and potential piping collapse, while soils with very low permeability diminish seepage but may create differential pressures. Analytical methods utilizing Darcy's law and flow net analysis are frequently employed to forecast uplift pressure distribution for specified permeability values. Contemporary practice employs numerical models utilizing finite element methods to mimic intricate seepage circumstances, thereby optimizing design and evaluating performance under fluctuating hydraulic loads. Consequently, assessing permeability is essential for comprehending subsurface flow dynamics, engineering secure hydraulic structures, and ensuring enduring stability against seepage-induced uplift forces.

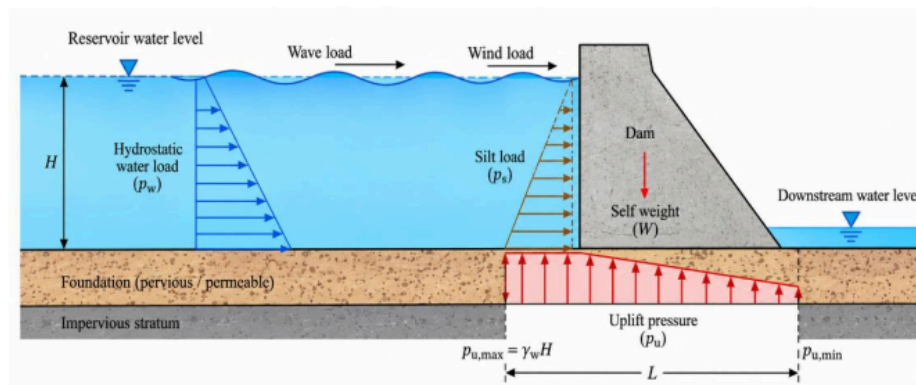


Figure 1.2 Uplift pressure beneath a dam

1.4.3 Groundwater contamination by leachate of solid waste in landfill

The assessment of permeability is a crucial technical parameter in evaluating groundwater contamination concerns resulting from leachate migration from solid waste landfills. Permeability determines the velocity at which leachate, a liquid produced by the breakdown of waste and infiltrating precipitation, penetrates the underlying soil strata toward the groundwater table. Soils with elevated permeability facilitate the rapid transport of contaminants, including heavy metals, organic compounds, and pathogens, hence augmenting the risk of groundwater contamination. In contrast, low-permeability materials like clay or compacted liners serve as natural barriers that impede the movement of contaminants. Consequently, engineers assess the permeability of subsoil and liner materials by laboratory testing, including constant head and decreasing head methods, or through in-situ tests such as pumping and infiltration tests. The results inform the design of designed liners, leachate collection systems, and monitoring wells to mitigate environmental risks. Mathematical models utilizing Darcy's law and pollutant transport equations employ permeability data to forecast plume migration and evaluate long-term concerns. Contemporary landfill engineering employs composite liners that integrate clay and geomembranes, engineered for minimal permeability to comply with regulatory requirements and safeguard groundwater. Therefore, precise assessment of permeability is crucial for analyzing subsurface flow, enhancing landfill design, and protecting groundwater resources from leachate-related contamination.

1.4.4 Differential settlement due to different permeability of soil under the foundation

The assessment of permeability is essential for analyzing and mitigating differential settlement of structures due to fluctuations in soil permeability beneath foundations. Differential settlement transpires when several sections of a structure settle inconsistently due to heterogeneous seepage, consolidation, or drainage properties of the underlying soil strata. Permeability governs the velocity of water transport and consolidation in saturated soils; thus, any change in this quality over the foundation area might result in unequal pore pressure dissipation, causing uneven settlement. The precise evaluation of soil permeability by laboratory testing, including constant head and falling head methods, or field tests such as pumping and permeability assessments, enables engineers to analyze probable settlement behavior under hydraulic and loading conditions. In fine-grained soils, poor permeability hinders consolidation, while in coarse-grained soils, swift

draining leads to expedited settlement. Engineers utilize this data to build appropriate foundation systems, such as raft or pile foundations, and employ soil enhancement techniques like grouting, preloading, or drainage installation to mitigate settlement. Permeability data facilitates numerical modeling and forecasting of settlement patterns under diverse load and moisture conditions. Consequently, the assessment of permeability not only aids in the analysis of subsurface drainage and consolidation rates but also is essential for maintaining the structural integrity, functionality, and durability of foundations by reducing the likelihood of differential settlement.

1.4.5 Stability of the slopes and the retaining structures

The evaluation of permeability is essential for evaluating slope stability and the efficacy of retaining structures, since it regulates water circulation through soil masses and directly affects pore water pressure development. In slopes, elevated permeability facilitates swift drainage, decreases pore pressure, and augments shear strength, so improving stability. In contrast, low-permeability soils store water, resulting in increased pore pressures and diminished effective stress, which may precipitate slope failures, particularly during intense rainfall or rapid drawdown scenarios. In retaining structures like earth-retaining walls, embankments, and reinforced soil slopes, the permeability of backfill and foundation materials influences the extent of hydrostatic pressure exerted on the structure. Assessing permeability via laboratory tests (constant head, falling head) and field methods (pumping tests, permeability tests) allows engineers to devise effective drainage systems, including weep holes, filter layers, and geosynthetic drains, to manage seepage and alleviate excess pore pressures. Analytical and numerical modeling of permeability data facilitates the prediction of seepage flow trajectories and the evaluation of stability under diverse hydraulic conditions. Incorporating precise permeability values enables engineers to enhance the design of slopes and retaining structures, so ensuring safety, reducing deformation, and averting catastrophic failures. Consequently, assessing permeability ²⁹ is essential in geotechnical engineering for the evaluation, construction, and maintenance of secure and lasting earth-retaining structures.

1.5 Significance of Heterogeneity

Heterogeneity in porous media refers to the spatial variation of physical, structural, and compositional properties within the soil mass. In natural and engineered systems, such variations may arise from differences in grain size, mineral composition, pore geometry,

stratification, compaction, and material arrangement. These variations directly influence the movement of water because zones with comparatively high hydraulic conductivity provide easier flow paths, whereas less permeable regions tend to restrict or redirect seepage. As a result, the hydraulic response of a heterogeneous medium cannot always be represented accurately by assuming uniform soil properties. In stratified porous media, the overall hydraulic behaviour is strongly affected by the properties and arrangement of individual layers. The thickness, sequence, and orientation of the layers may alter the continuity of flow paths and can produce different hydraulic responses in horizontal and vertical directions. Therefore, understanding the influence of stratification is important for the realistic assessment of seepage, groundwater movement, drainage, contaminant transport, and the performance of hydraulic and environmental systems.

Apart from natural stratification, the hydraulic behaviour of porous media can also be modified through external interventions. Chemical admixtures may alter pore spaces, particle arrangement, and connectivity, while microbiological activity can modify flow passages through processes such as pore occupation and biofilm formation. Although earlier studies have investigated the individual influence of chemical and microbiological treatments on hydraulic conductivity, comparatively limited information is available on their combined effect in heterogeneous stratified porous media. The interaction of these modifications with layer orientation further increases the complexity of the flow mechanism. Considering these aspects, there is a need to systematically examine how chemical admixtures, microbiological culture, and layer inclination influence the hydraulic conductivity of heterogeneous porous media. These considerations establish the need to evaluate the effects of chemical admixture, microbiological culture, and layer inclination on the hydraulic conductivity of heterogeneous porous media, thereby providing a clear basis for the objectives of the present study.

1.6 Chemical and microbiological modification of porous media

The hydraulic behaviour of heterogeneous porous media can be significantly influenced by changes in the composition and internal pore structure of the soil mass. In the present study, chemical and microbiological modifications are introduced to examine their effect on horizontal hydraulic conductivity. Fly ash is used as the chemical admixture and is mixed with the soil in varying proportions. Owing to its fine particle size, fly ash can enter and occupy part of the existing pore spaces, thereby altering pore connectivity and

increasing the resistance offered to water flow. In addition, *Bacillus subtilis* is used as the microbiological culture at different bacterial cell densities. The presence and growth of bacterial cells within the soil matrix can modify the available flow passages through pore occupation, biofilm development, and associated biological activity. These changes may reduce the effective cross-sectional area available for seepage and influence the continuity of interconnected pores. The combined use of fly ash and bacterial culture creates additional variability within the stratified porous medium and allows the hydraulic response to be examined under different treatment conditions. In this way, the chemical and microbiological interventions represent controlled modifications to the porous system rather than changes in the basic soil layering alone. Their influence is evaluated together with the orientation of the stratified layers to understand how material modification and structural arrangement affect water movement. This approach provides a clearer basis for studying changes in hydraulic conductivity under heterogeneous conditions and supports the objectives concerning chemical and microbiological effects.

1.7 Objectives of the study

The primary objective of this work is to empirically examine the hydraulic conductivity of heterogeneous porous media. The objectives of this investigation are:

- To study the effect of chemical admixture on hydraulic conductivity of heterogeneous media.
- To study the effect of microbiological culture (bacterial) on hydraulic conductivity of heterogeneous media.
- To analyse the effect of inclination of layers on hydraulic conductivity of heterogeneous porous media including chemical and microbiological interventions.

1.8 Organization of the thesis

This thesis comprises five chapters, including an introductory chapter. Chapter II presents an exhaustive examination of relevant literature concerning fluid dynamics in homogeneous and heterogeneous stratified porous media. Chapter III presents a detailed description of the experimental configuration and procedure for the porous media, along

with the analytical methodologies employed. Chapter IV presents an analysis and discussion of the results obtained from experimental research. The final chapter contains the findings of the study. Chapter V additionally includes recommendations ⁶² for future research.

CHAPTER 2

REVIEW OF LITERATURE

2.1 General

³⁰ Flow through porous media is strongly influenced by the internal structure and spatial variability of the medium. In natural soils and geological formations, differences in particle size, pore arrangement, stratification, mineral composition, and biological activity can produce substantial variations in hydraulic conductivity. Such heterogeneity may alter flow paths, promote preferential movement, and create anisotropic hydraulic behaviour. These effects are particularly important in layered soils, where the sequence, thickness, and orientation of individual strata govern the effective movement of water through the porous system.

The hydraulic behaviour of porous media can also be modified by external interventions. Chemical additives may alter pore geometry and connectivity, whereas microbial activity can modify the pore network through mechanisms such as biofilm development, pore occupation, and biomineralization. These processes may considerably reduce hydraulic conductivity and are therefore relevant to seepage control, groundwater protection, soil improvement, and other geotechnical and environmental applications.

Accordingly, previous research on hydraulic conductivity has developed along several interconnected themes, including flow through stratified and anisotropic soils, influence of layer arrangement and orientation, chemical modification of porous media, microbial-induced permeability changes, and prediction of hydraulic conductivity using analytical, numerical, and data-driven approaches. Particular attention has also been given to experimental methods for evaluating horizontal and vertical hydraulic conductivity and to the challenges associated with representing heterogeneous media using conventional permeability relationships.

The following section reviews these developments in a systematic manner. The major studies relevant to the present research are summarized chronologically in Table 2.1, with emphasis on their research focus, methodology, and principal findings. This organization helps identify how understanding of heterogeneous porous media has evolved and establishes the research gaps addressed in the present investigation.

2.2 Review of previous studies on hydraulic conductivity in stratified and heterogeneous porous media

Table 2.1 presents the development of research on hydraulic conductivity and flow through stratified and heterogeneous porous media over several decades. When the studies are considered chronologically, they reveal a clear shift from the investigation of basic soil and pore-scale controls on permeability to more complex questions involving anisotropy, stratification, chemical modification, microbiological activity, layer orientation and, more recently, data-driven prediction. The value of the table therefore lies not only in listing individual studies, but also in showing how successive investigations have addressed separate components of a broader problem while leaving important interactions insufficiently explored. The following discussion interprets this progression and uses it to establish the logical basis for the present research.

Early investigations concentrated on the physical controls governing permeability. Meegoda et al. (1980) examined permeability estimation in anisotropic media and showed that variables related to specific surface area, void ratio, particle shape and particle arrangement can be used to represent the hydraulic response of soils. This work was important because it moved permeability analysis beyond a single bulk soil parameter and toward a description based on internal fabric. Witt and Brauns (1983)

extended this understanding by explicitly considering particle orientation and the difference between flow parallel and perpendicular to the preferred direction of the soil structure. Their work linked permeability, porosity and tortuosity and demonstrated that directional differences in pore geometry can produce measurable anisotropy. Tavenas et al. (1983) further showed that, in intact soft clays, permeability is not controlled by void ratio alone but is also associated with plasticity and soil fabric. Together, these studies established a fundamental point: hydraulic conductivity is a structural property of the porous medium and may vary with direction even when the soil appears macroscopically uniform.

The next group of studies examined how material state and fabric modification influence flow. Wang and Huang (1984) investigated the permeability-compaction relationship for soil liners and developed correlations involving maximum dry density, optimum moisture content and permeability. Their results emphasized that construction-related changes in density and moisture condition can substantially alter the connected pore network. Kenney et al. (1984) examined particle size, shape and gradation and concluded that the finer fraction can exert a dominant control on pore channels and therefore on permeability. Al-Tabba and Wood (1987), using measurements of both vertical and horizontal permeability in kaolin clay, reported a marked difference between the two directions and showed that consolidation affects the directional components of hydraulic conductivity differently. These findings collectively reinforced the concept that permeability depends on the evolving internal geometry of the soil, not merely on its classification or average porosity.

Research subsequently moved from single or effectively uniform materials toward layered systems. Selim (1988) analysed two-dimensional flow through layered soil with inclined interfaces, thereby introducing the effect of orientation into the representation of stratified media. Stephens and Heermann (1988) investigated permeability anisotropy in stratified sands and found that effective anisotropy could exceed that inferred from the individual layers. This observation is particularly significant because it shows that the hydraulic behaviour of a composite medium cannot always be obtained by simply combining the properties of its constituents. Samani et al. (1989) examined wetting-front instability in fine-over-coarse layered systems and showed that a sufficiently large contrast between layers can lead to fingered or preferential flow. Khan et al. (1989) compared observed and computed phreatic surfaces in two- and three-layer soil systems

and demonstrated that layered drainage behaviour can be represented successfully when the arrangement of the strata is considered. Yeh and Harvey (1990) highlighted the importance of averaging procedures in layered sands, while Sharma (1991) showed that the permeability of the lower layer strongly influences drain spacing. Thus, by the early 1990s, the literature had clearly established that layer sequence, property contrast and orientation are essential controls on flow in heterogeneous deposits.

Later work provided stronger experimental evidence for directional and layered effects. Burger and Belitz (1997) estimated horizontal and vertical hydraulic conductivity in layered sediments using field and laboratory methods and reported higher values in cores oriented parallel to bedding, with K_h/K_v ratios greater than unity. Their results directly confirmed the anisotropic behaviour expected from stratification. Yuzhen et al. (1999) demonstrated that confining pressure can modify the permeability of soil-cement mixtures, illustrating that hydraulic conductivity may also change under stress. Sridharan and Prakash (2002) then argued that ²the equivalent permeability of stratified deposits cannot always be obtained by a straightforward application of Darcy-based averaging because the exit layer and interactions among layers can influence the measured response. Abulrajah et al. (2005) compared field and laboratory techniques for horizontal permeability of marine clay, further highlighting the need for appropriate measurement methods. These studies are particularly relevant to the present work because they demonstrate both the importance of horizontal flow and the difficulty of assigning a single representative hydraulic conductivity to a heterogeneous medium.

The role of internal arrangement became more explicit in later stratified-soil studies. Alam et al. (2015) showed that the properties of the interface and the underlying layer can significantly affect permeability in a two-layer system. Gupta et al. (2016) further demonstrated that the position and thickness of layers in clay-sand systems can substantially modify the measured permeability. Sharo et al. (2021) investigated the combined effects of stratification and flow direction and found that the order of the layers contributes strongly to deviations between experimental and theoretical equivalent permeability. These findings show that heterogeneous porous media exhibit an interaction between material properties and geometry. A layer does not contribute to the total hydraulic response only through its own conductivity; its location, thickness, orientation, and hydraulic connection with adjacent layers can change the continuity and resistance of the overall flow path. This is an important basis for studying inclined

stratification, because even small geometric changes may redirect flow through portions of the medium having different resistances.

A parallel branch of research examined the deliberate modification of porous media using mineral or chemical additives. Shenbaga and Gayathri (2004) studied the permeability behaviour of fly ash and highlighted the influence of void ratio and hydraulic conditions on its flow response. Ayininuola et al. (2013) investigated rice husk ash and reported that permeability decreased as the additive content increased, a behaviour associated with pore filling and stronger bonding. Mazzieri and Emidio (2015) examined a dense prehydrated geosynthetic clay liner and demonstrated that engineered barrier materials can achieve very low hydraulic conductivity under suitable hydration conditions. Zhou et al. (2019) later showed that chemical solutions can be used to form a low-permeability zone in sand through precipitation of metal-organic complexes. In the context of the present thesis, these studies are important because they demonstrate that chemical intervention can change pore size, pore continuity and resistance to flow. However, the majority of such studies treated chemical modification as the principal variable and did not simultaneously investigate its interaction with microbial activity and inclined stratification.

Another important research stream concerns the use of microorganisms to alter soil hydraulic behaviour. Ivanov and Chu (2008) presented microbial geotechnology as a means of modifying engineering properties through processes such as bioclogging and biocementation. Their synthesis showed that microbial growth can reduce porosity and hydraulic conductivity, while biomineralization can improve strength. Brovelli et al. (2009) further emphasized that biofilm formation changes pore geometry and can obstruct both fluid and nutrient transport. Umar et al. (2016) reviewed the role of microorganisms and biomineralization in soil improvement and documented reductions in permeability reported across different studies. Khaleghi and Rowshanzamir (2019) similarly described how biofilm development can block pore space and reduce flow. Chen et al. (2021) provided direct experimental evidence of a substantial decrease in the hydraulic conductivity of remoulded loess after microbial activity developed. Arpajirakul et al. (2021) also demonstrated that the effectiveness of microbially induced processes depends on treatment conditions and the ability of nutrients and reactants to move through the soil. These studies established the physical plausibility of microbial control

of seepage, but they also reveal that the microbial effect is strongly dependent on the surrounding pore network and transport conditions.

The microbial literature therefore cannot be considered independently of heterogeneity. Biofilm growth, bacterial occupation and biomineral precipitation occur within existing pore pathways; consequently, their hydraulic effect should depend on where high- and low-conductivity zones are located and on how the primary flow direction intersects the layered structure. Yet most microbial studies summarized in Table 2.1 focused on the biological mechanism itself, on homogeneous or comparatively simple media, or on vertical flow configurations. At the same time, the stratified-media studies largely treated layer geometry and hydraulic anisotropy without simultaneously incorporating a microbiological modification. This separation in the literature creates a conceptual gap: the effect of microbial clogging in an inclined, heterogeneous and chemically modified medium cannot be inferred reliably by simply combining conclusions from independent studies. The interaction must be examined directly because the competing effects of layer orientation, preferential flow, pore filling and biological obstruction may alter both the magnitude and direction of the hydraulic response.

With the increasing complexity of the governing variables, recent research has also moved toward machine-learning and data-driven prediction. Gupta et al. (2024) investigated prediction of hydraulic conductivity in fly-ash-modified stratified media using Gene Expression Programming, Artificial Neural Networks and Regression Tree models, and reported strong performance of the ANN while also proposing a predictive expression for horizontal hydraulic conductivity. Gupta and Srivastava (2025) investigated ³² the influence of *Bacillus subtilis* on horizontal permeability of stratified porous media at different orientation angles and coupled the experiments with machine-learning prediction and statistical evaluation. Their results showed that bacterial presence reduced hydraulic conductivity because of biofilm formation and pore blocking, while conductivity still tended to increase with orientation angle. The inclusion of machine learning in these studies reflects a broader methodological shift: once soil properties, treatment intensity, bacterial density, layer geometry and flow direction act simultaneously, the resulting relationship becomes sufficiently nonlinear that simple empirical equations may not capture all interactions.

Table 2.1 Summary of previous studies on hydraulic conductivity and flow behaviour in stratified and heterogeneous porous media

Year	Authors	Research Focus	Methodology	Key Findings
1980	Meegoda et al.	Permeability estimation in anisotropic media	Proposed analytical expression using variables (specific surface area, void ratio, particle shape/arrangement); validated via lab tests on fine sand	Predicted permeability values were very close to observed values.
1983	Witt and Brauns	Effect of particle shape/orientation on permeability (parallel vs perpendicular flow)	Theoretical derivation linking permeability–porosity–tortuosity; supported with experiments	Permeability ratio in different directions equals square of reciprocal tortuosity ratio; experiments matched theory.
1983	Tavenas et al.	Permeability of intact soft clays vs void ratio	Experiments for flow perpendicular direction; semi-log representation	Permeability depends on void ratio, plasticity index, and clay fabric (complex function).
1984	Wang and Huang	Permeability–compaction relationship for soil liners	Constant head and falling head tests on mixed material; regression correlations	Developed models linking MDD, OMC, and permeability; recommended for prediction with reasonable accuracy.
1984	Kenney et al.	Role of particle size/shape/gradation on permeability	Constant head tests on soils with varying size/shape	Shape/gradation had negligible effect compared to small particle size; small particles control pore channels and permeability.
1987	Al-Tabba and Wood	Vertical vs horizontal permeability of kaolin clay	Modified oedometer to measure both K_v and K_h	K_v decreased faster due to 1D consolidation; $K_h \approx 3 \times K_v$; both uniquely related to void ratio.
1988	Selim	2D flow in layered soil with inclined surfaces	Analytical solution assuming multiple horizontal layers with flow normal to bedding	Anisotropy influence was greatest when the top layer was anisotropic.

1988	Stephens and Heerman	Saturation effect on permeability anisotropy in stratified sand	Infiltration experiments in alternating coarse/fine packed layers	Nonlinearity of discharge–gradient used as anisotropy measure; effective anisotropy higher than that computed from individual layers.
1989	Samani et al.	Wetting front instability in layered soils (fine over coarse)	Conceptual/experimental observation of infiltration behavior	Flow stayed 1D up to K-ratio ≈ 20 ; beyond that, finger/column flow developed.
1989	Khan et al.	Verification of Toksoz & Kirkham model for layered recharge/drainage	Experimental verification for 2- and 3-layered soils; compared phreatic surfaces	Observed vs computed phreatic surfaces matched closely; model suitable for layered drainage problems.
1990	Yeh and Harvey	Permeability measurement in unsaturated layered sands; averaging techniques	Measured permeability in layered coarse/medium sand	Theoretical and experimental values showed good agreement; averaging method significance highlighted.
1991	Sharma	Drain spacing design in two-layer soils	Analytical design approach; compared predicted vs observed	Lower-layer K strongly affects drain spacing; predictions matched observations well.
1992	Shamsai and Marino	Artificial recharge in multilayer anisotropic media (radial flow)	Numerical investigation	Higher anisotropy produced greater inflow.
1994	Ronald et al.	Preferential flow along grout–clay interface	Two tests using stratified clay with cemented borehole	Both tests indicated preferential interface flow.
1995	Okagbue	Influence of sand stratification arrangement on permeability	Permeability measured perpendicular to stratification	Highest permeability when fine fraction placed at the end; lowest for unsorted/mixed fractions.
1997	Burger and Belitz	Field + lab estimation of K_h and K_v in layered sediments	Undisturbed sampling (split barrel core); tested vertical and horizontal cores	90% parallel-oriented cores showed higher K; $K_h/K_v \approx 1.33\text{--}1.57$.

1999	Yuzhen et al.	Permeability of soil–cement mixtures under confining pressure	Custom permeameter; vertical flow; applied confining pressure; proposed relation using consolidation coefficient	K increased at low confining pressure but decreased at high pressure; very low K ($\sim 10^{-8}$ cm/s).
2002	Sridharan and Prakash	Equivalent permeability of stratified deposits (layer interaction)	Theoretical interpretation of flow through stratified media	Equivalent K cannot be computed by Darcy's equation alone; in vertical flow, exit layer controls deviation from theoretical K.
2004	Shenbagha and Gayathri	Permeability behavior of fly ash (Dadri TPP)	Studied effect of head loss and void ratio on permeability	Head loss variation had only a small effect on permeability.
2005	Abulrajah et al.	Horizontal permeability of marine clay for land reclamation	Field tests: BAT, Dilatometer, CPTU; compared with lab	BAT readings were most reliable and close to laboratory results.
2008	Ivanov and Chu	Microbial geotechnology applications: bioclogging and biocementation to alter soil properties	Review / concept synthesis	Bioclogging reduces porosity and hydraulic conductivity; biocementation increases shear strength; highlights interdisciplinary needs and that many studies are still lab-scale.
2009	Walker and Indraratna	Pore pressure response of multilayer soils	Spectral method analysis	Permeability and compressibility varied linearly with depth within each layer.
2009	Brovelli et al.	Biofilm formation in porous media and its impact on porosity/permeability	Synthesis	Biofilms can change pore geometry and significantly reduce porosity/permeability, obstructing flow and nutrient transport.
2011	Lee et al.	Rainfall infiltration in unsaturated soils; comparison of 1D vs 2D models	Instrumented modelling: 1D soil column + 2D slope model	For homogeneous single-layer soils, 1D and 2D percolation rates are nearly identical; for two-layer systems, 2D is needed due to lateral flow.

2013	Ayininuola et al.	Effect of rice husk ash (RHA) on soil permeability	Laboratory testing on soil with RHA	Permeability decreases as RHA content increases due to pore filling and stronger bonding; RHA suggested for grouting/impermeability needs.
2013	Nagy et al.	Comparison of methods to estimate permeability coefficients in layered sands/silts	Field (Khafagi probe, Menard probe, water filtration) + Lab (constant/falling head) + Hazen equation	No universal method; each has validity limits; avoid mixing methods within one borehole/layer depth because method changes can exceed true soil variation.
2015	Mazzieri and Emidio	Hydraulic conductivity of dense prehydrated geosynthetic clay liner (DPH-GCL)	Permeability testing with water, seawater, and Ca-solution	DPH-GCL shows very low permeability to water; hydration at installation is a notable difference compared with conventional GCLs.
2015	Alam et al.	Role of interface/underlying layer properties in layered soils	Two-layer stratified soil testing	Permeability of layered samples is influenced by properties of the underlying layer; interface effects are significant.
2016	Gupta et al.	Effect of layer position and thickness in clay-sand two-layer systems	Experimental study on composite two-layer soils	Thickness of the end layer significantly affects permeability of stratified soils.
2016	Umar et al.	Microorganisms, biomineralization, and impacts on soil properties	Review	Summarizes factors controlling microbial activity and MICP; reports improvements in stiffness/strength and permeability reductions across studies.
2019a	Gupta et al.	Single-layer soil: experimental vs simulated permeability comparison	Experimental + simulation comparison	Experimental and simulated permeability values show very small discrepancy.

2019b	Gupta et al.	Double-layer soil: experimental vs simulated permeability comparison; blending effects	Experimental + simulation comparison	Blending leads to variations between measured and simulated permeability values.
2019	Tan et al.	Shear strength improvement in root-geomat reinforced soil (RMS)	Laboratory direct shear tests on geomat + Bermuda grass cultivated samples	Combined reinforcement (roots + geomats) significantly improves shear strength, especially at low normal stress.
2019	Zhou et al.	In-situ permeability reduction using chemical solutions	AlCl ₃ + humic acid treatment; stratification to form low-permeability layer; pumping tests	Treated sand permeability reduced to about 2% of original due to precipitation of metal-organic complexes forming a low-permeability layer.
2019	Khaleghi and Rowshan zamir	Biofilm effects on porosity/permeability	Laboratory Synthesis	Biofilms can clog pores and reduce flow by altering pore-space geometry.
2021	Sharo et al.	Effects of stratification and flow direction on equivalent permeability in layered soils	Falling head permeability with custom mold; downward/horizontal/upward flow	Layer order strongly contributes to deviations between experimental and theoretical equivalent permeability.
2021	Nasrabad i et al.	Predicting submerged hydraulic jump characteristics	GMDH modelling	⁴⁹ MDH used to forecast jump length, relative energy loss, and relative submergence depth.
2021	Chen et al.	Microbial activity effect on hydraulic conductivity of remolded loess	Laboratory tests with bacterial inoculation and carbon restriction	Initial permeability stable (0.14-0.16 m/day), then decreased by 81-93% to 0.01-0.05 m/day.

2021	Arpajirakul et al.	Optimizing MICP conditions to improve fine-grained soils	Lab MICP using <i>Sporosarcina pasteurii</i> ; sand clogging; fine-grained soils (kaolin/laterite/Bangkok clay)	Urea- Ca_2^+ rate of 7.5 mmol/h produced highest clogging; too high rate increases salinity/supersaturation and reduces effectiveness; nutrient transport limited in high-plasticity clay.
2022	Konstantinou and Bisconti n	Fluid injection and fracture formation in bio-cemented sands	Modified Hele-Shaw setup	Fracture type depends on cementation: higher cementation shifts fractures from cavity-like to crack-like.
2022b	Torabi et al.	Permeability prediction using transparent ML models	CART and GMDH	Both models shown reliable for estimating permeability; supports data-driven tools for complex water-engineering problems.
2022	Eryuruk	Hydraulic conductivity reduction via MICP in granular media	Column tests with glass beads (0.25-3 mm), <i>S. pasteurii</i> , 500 mM CaCl_2 + 500 mM urea under continuous flow	Hydraulic conductivity decreases due to CaCO_3 precipitation; lowest K achieved with smallest beads (0.25 mm) and highest cell density.
2023	Li et al.	Modified Kozeny-Carman equation for hydraulic conductivity estimation	Theoretical derivation using Poiseuille's law; introduces 2D porosity and correction coefficient	Revised Kozeny-Carman formulation better suited for estimating K in clay and sand compared with existing theoretical equations.
2023	Zhao et al.	Low-permeability soils: pollutant migration and remediation options	Review / synthesis	Reviews remediation methods (electrokinetic, polymer flushing, fracturing, in-situ thermal); argues single-tech solutions often insufficient, recommending integrated approaches.

2023	Ma et al.	Effect of sample preparation on permeability and microstructure of remolded loess	Experimental comparison of preparation methods (pre-wetting)	Pre-wetting reduces uniformity (especially at higher initial water content), causes stronger pore-structure changes and higher permeability coefficients.
2023	Azarhoo sh and Koohmis hi	Predicting hydraulic conductivity of coarse granular material	Random Forest vs ANN and ANFIS	Random Forest performed robustly; statistical comparison supports ML-based indirect prediction of hydraulic conductivity.
2024	Wang et al.	Treated wastewater irrigation effects on soil hydraulic properties	Soil assessment under TWW irrigation	High salts may cause salinization/sodification and degrade structure; medium-textured soils show salt build-up and enhanced K, while fine-textured soils risk clogging.
2024	Gupta et al.	Predicting hydraulic conductivity in stratified media after chemical modification	ML models (GEP, ANN, RT) + proposed equation	ANN best predicted horizontal hydraulic conductivity; proposes a new equation for horizontal K applicable to stratified media.
2025	Gupta and Srivastava	Influence of Bacillus subtilis on horizontal permeability of stratified porous media under different orientation angles; use of ML to predict horizontal permeability coefficient	Laboratory experiments on stratified media at multiple orientations + Machine learning prediction + Statistical performance evaluation	Bacterial presence causes significant reduction in hydraulic conductivity due to biofilm formation and pore blocking; higher bacterial density leads to greater reduction. Permeability increases with orientation angle (likely due to altered flow pathways), but bacterial clogging remains dominant. GEP achieved the best prediction accuracy, outperforming other models on statistical metrics.

The above table shows that the main components governing hydraulic conductivity are already recognized in the literature, but they have largely been developed in separate research pathways. The first pathway established the effects of pore structure, particle arrangement, void ratio and anisotropy. The second demonstrated the importance of layering, layer order, interface effects, thickness and flow direction. The third showed that chemical or mineral additives can reduce conductivity through pore filling, densification or precipitation. The fourth established that microbial activity can reduce conductivity through pore occupation, biofilm development and bioclogging. The fifth introduced numerical and machine-learning approaches to represent increasingly nonlinear hydraulic behaviour. What remains comparatively less developed is an integrated experimental framework in which these mechanisms are allowed to act simultaneously. In particular, there is limited systematic evidence on how a chemical additive and bacterial treatment interact within an inclined stratified medium while the response is measured specifically in the horizontal direction.

The logical research gap arising from the reviewed studies is therefore not simply that 'more work is required' on hydraulic conductivity. The gap is more specific. First, earlier investigations predominantly examined heterogeneity, chemical modification and microbiological modification as separate influences. Second, studies of stratified soils demonstrated strong effects of layer orientation and flow direction, but these geometric effects were rarely studied together with simultaneous chemical and biological alteration. Third, conventional permeability research has placed greater emphasis on vertical testing, whereas horizontal conductivity in layered media is particularly relevant to preferential flow and anisotropic behaviour and lacks a universally standardized laboratory procedure. Fourth, many earlier experiments used relatively small specimens or restricted flow configurations, limiting the ability to examine the combined influence of treatment and layer inclination under a broader controlled geometry. Finally, once several variables act simultaneously, the response may become nonlinear, creating a need for reliable predictive methods in addition to physical experimentation.

Accordingly, the present investigation is justified by the need to evaluate horizontal hydraulic conductivity in a heterogeneous stratified porous medium while controlling three interacting factors: chemical modification using fly ash, microbiological modification using *Bacillus subtilis*, and the inclination of the soil layers. By varying fly ash content, bacterial cell density and orientation within the same experimental

programme, the study is able to distinguish the individual effects of each factor and, more importantly, evaluate their combined influence. The use of a comparatively large custom horizontal permeameter provides a controlled platform for observing these interactions over a larger flow path than that available in conventional small permeability cells. The accompanying data-driven modelling further allows the experimentally observed nonlinear behaviour to be represented and assessed quantitatively. Thus, the research gap identified from Table 2.1 leads directly and logically to the objectives, experimental design and predictive analysis adopted in the thesis.

2.3 Literature gaps

Based on the critical review of previous investigations summarized in Table 2.1, the following research gaps are identified.

1. Limited investigation of the combined influence of chemical modification, microbiological treatment, and soil heterogeneity on hydraulic conductivity.

Previous studies have generally examined these factors independently. Chemical modification studies, such as Ayininuola et al. (2013), Zhou et al. (2019), and Gupta et al. (2024), demonstrated that mineral or chemical additives can reduce hydraulic conductivity through pore filling, densification, precipitation, and alteration of pore connectivity. In contrast, microbiological studies including Ivanov and Chu (2008), Brovelli et al. (2009), Umar et al. (2016), Khaleghi and Rowshanzamir (2019), and Chen et al. (2021) established that microbial growth, biofilm development, biomineralization, and pore occupation can significantly modify permeability. However, these two lines of research have largely progressed independently, and comparatively little attention has been given to the simultaneous action of a chemical admixture and bacterial treatment in heterogeneous stratified porous media. The literature itself identifies this separation as a conceptual gap because the interaction of pore filling and biological clogging cannot be reliably inferred by simply combining results obtained from independent studies.

2. Insufficient understanding of microbiologically induced changes in hydraulic conductivity under inclined and heterogeneous layered conditions.

Studies by Ivanov and Chu (2008), Brovelli et al. (2009), Umar et al. (2016), Khaleghi and Rowshanzamir (2019), and Chen et al. (2021) demonstrated the ability of

microorganisms and biofilms to reduce porosity and hydraulic conductivity. Nevertheless, most of these studies focused mainly on the microbial mechanism itself, relatively simple or homogeneous porous media, or conventional flow configurations. In comparison, stratified-media investigations primarily considered layer geometry, anisotropy, and flow direction without simultaneously incorporating microbiological alteration. Consequently, the influence of bacterial clogging within inclined heterogeneous strata, where preferential flow and layer orientation may interact with biological obstruction, remains insufficiently investigated.

3. Limited experimental investigation of layer inclination together with chemical and microbiological modifications.

Earlier studies clearly established that stratification and flow direction influence equivalent hydraulic conductivity. For example, Selim (1988) investigated two-dimensional flow in layered soil with inclined interfaces, while Stephens and Heermann (1988) demonstrated enhanced anisotropic behaviour in stratified sands. Burger and Belitz (1997) reported differences between horizontal and vertical hydraulic conductivity, and Sharo et al. (2021) showed that layer order and flow direction substantially influence deviations between experimental and theoretical equivalent permeability. These investigations confirm the importance of layer arrangement and orientation; however, the geometrical effects of inclination have rarely been studied together with simultaneous chemical and biological alteration. Therefore, the interaction among layer inclination, chemical pore modification, microbial clogging, and horizontal flow remains inadequately understood. This limitation is specifically recognized in the reviewed literature, where geometric effects were generally investigated separately from chemical and microbiological modification.

4. Horizontal hydraulic conductivity of modified stratified porous media has received comparatively less attention than conventional vertical permeability.

A substantial portion of traditional permeability research has emphasized vertical or flow-normal-to-layer testing. For example, Tavenas et al. (1983) examined flow perpendicular to soft clay specimens; Okagbue (1995) studied permeability perpendicular to stratification; and Yuzhen et al. (1999) employed vertical flow through soil–cement mixtures. Although studies such as Al-Tabba and Wood (1987), Burger and

Belitz (1997), and Abulrajah et al. (2005) considered horizontal permeability, systematic studies of horizontal flow through chemically and microbiologically modified inclined stratified media remain limited. This is important because horizontal hydraulic conductivity is particularly relevant to preferential flow and anisotropic seepage in layered deposits. The review further indicates that horizontal conductivity in layered media has not received the same level of standardized experimental investigation as conventional permeability testing.

5. Previous experimental studies have generally employed restricted specimen dimensions or limited flow configurations.

Several previous investigations were conducted using conventional permeability cells, soil columns, modified oedometers, or relatively restricted laboratory arrangements. Such configurations are suitable for assessing individual mechanisms but provide limited scope for examining the combined effect of heterogeneity, treatment intensity, and layer inclination over an extended horizontal flow path. The review therefore identifies a need for experiments conducted using a comparatively large-scale controlled horizontal permeameter, in which layer orientation, chemical dosage, and bacterial concentration can be varied systematically. The present study addresses this limitation using a custom horizontal permeameter capable of examining these interactions over a larger flow path.

6. Limited predictive frameworks are available for the simultaneous nonlinear effects of chemical, biological, and geometrical parameters.

Recent studies have begun applying data-driven techniques to hydraulic conductivity prediction. Gupta et al. (2024) employed GEP, ANN, and RT models for chemical modified stratified media, while Gupta and Srivastava (2025) combined experiments on *Bacillus subtilis*-treated stratified media with machine-learning prediction and statistical evaluation. These studies demonstrate that machine-learning methods can effectively represent nonlinear hydraulic responses. However, when soil characteristics, fly ash content, bacterial density, layer orientation, and flow direction act simultaneously, the hydraulic response becomes considerably more complex. Accordingly, there remains a need for predictive models capable of representing the combined nonlinear influence of chemical, microbiological, and geometrical parameters on horizontal hydraulic conductivity.

2.4 Summary of literature review

The literature reviewed in this chapter shows that hydraulic conductivity in porous media is governed not only by basic soil properties but also by stratification, anisotropy, layer sequence, pore structure, and flow direction. Previous studies on layered soils have demonstrated that the thickness, position, and arrangement of individual layers can considerably influence equivalent hydraulic conductivity, and that experimentally observed values may differ from theoretical estimates because of interface effects and directional flow behaviour. Studies related to chemical modification have further shown that the addition of fine or reactive materials can alter pore geometry and reduce permeability through pore filling, densification, or precipitation processes. Similarly, microbiological investigations have established that bacterial activity can modify hydraulic behaviour through biofilm formation, pore occupation, and bioclogging, resulting in substantial reductions in hydraulic conductivity. The reviewed studies also indicate that the magnitude of microbial influence depends on bacterial density, soil characteristics, and prevailing transport conditions.

Although considerable work has been carried out on stratified soils, chemical modification, and microbial treatment individually, comparatively limited attention has been given to their combined influence in heterogeneous porous media. In particular, the interaction between chemical admixtures, microbiological culture, and the inclination of stratified layers remains insufficiently explored. Earlier investigations have also largely been conducted using relatively small laboratory systems or under restricted orientations, which limits understanding of hydraulic behaviour under more representative heterogeneous conditions. These limitations form the principal research gaps identified in the present review.

Therefore, the literature establishes a clear need for a systematic investigation of hydraulic conductivity in heterogeneous stratified porous media under chemical and microbiological modification and varying layer orientations. The present study addresses these gaps through controlled experimental investigation and further evaluates the capability of data-driven approaches for predicting horizontal hydraulic conductivity. Thus, the reviewed literature provides the scientific foundation and justification for the objectives and methodology adopted in this thesis.

CHAPTER 3

MATERIAL AND METHODS

3.1 General

This chapter presents the overall methodology adopted to investigate the horizontal hydraulic conductivity of heterogeneous stratified porous media under different treatment and orientation conditions. The experimental programme was designed to examine the influence of chemical modification using fly ash, microbiological treatment using *Bacillus subtilis*, and variation in the inclination of soil layers. A custom-designed horizontal permeameter was used to conduct the laboratory experiments under controlled conditions so that the effect of each parameter could be assessed systematically. The chapter describes the experimental arrangement, preparation of soil specimens, incorporation of fly ash, preparation of bacterial suspensions, and testing of layered media at different orientation angles. The methodology also includes the theoretical basis used for evaluating hydraulic conductivity and the procedures adopted for analysing the observed flow behaviour. In addition to the experimental investigation, a Support Vector Regression (SVR) model was employed to estimate horizontal hydraulic conductivity using the relevant input variables obtained from the experimental programme. ¹³ The predictive performance of the model was evaluated through appropriate statistical indicators by comparing the predicted and measured values. Thus, the chapter provides a concise description of the complete methodological framework adopted in the study, integrating laboratory experimentation, theoretical analysis, and data-driven prediction. The procedures presented in this chapter form the basis for interpreting the influence of material modification, microbial activity, and layer inclination on flow through heterogeneous porous media and support the results and discussion presented in the subsequent chapter.

Figure 3.1 presents the overall methodology adopted in the present investigation. The research programme begins with identification of the research problem and characterization of the soil, fly ash, and microbiological culture. This is followed by preparation of heterogeneous stratified porous media and experimental evaluation of the effects of chemical admixture, bacterial treatment, and layer inclination on horizontal hydraulic conductivity. The experimental results are subsequently compared and analysed, followed by SVR-based predictive modelling and statistical evaluation. The methodological sequence has been structured to directly address the three research objectives and to establish the individual and combined influence of the selected parameters on hydraulic conductivity.

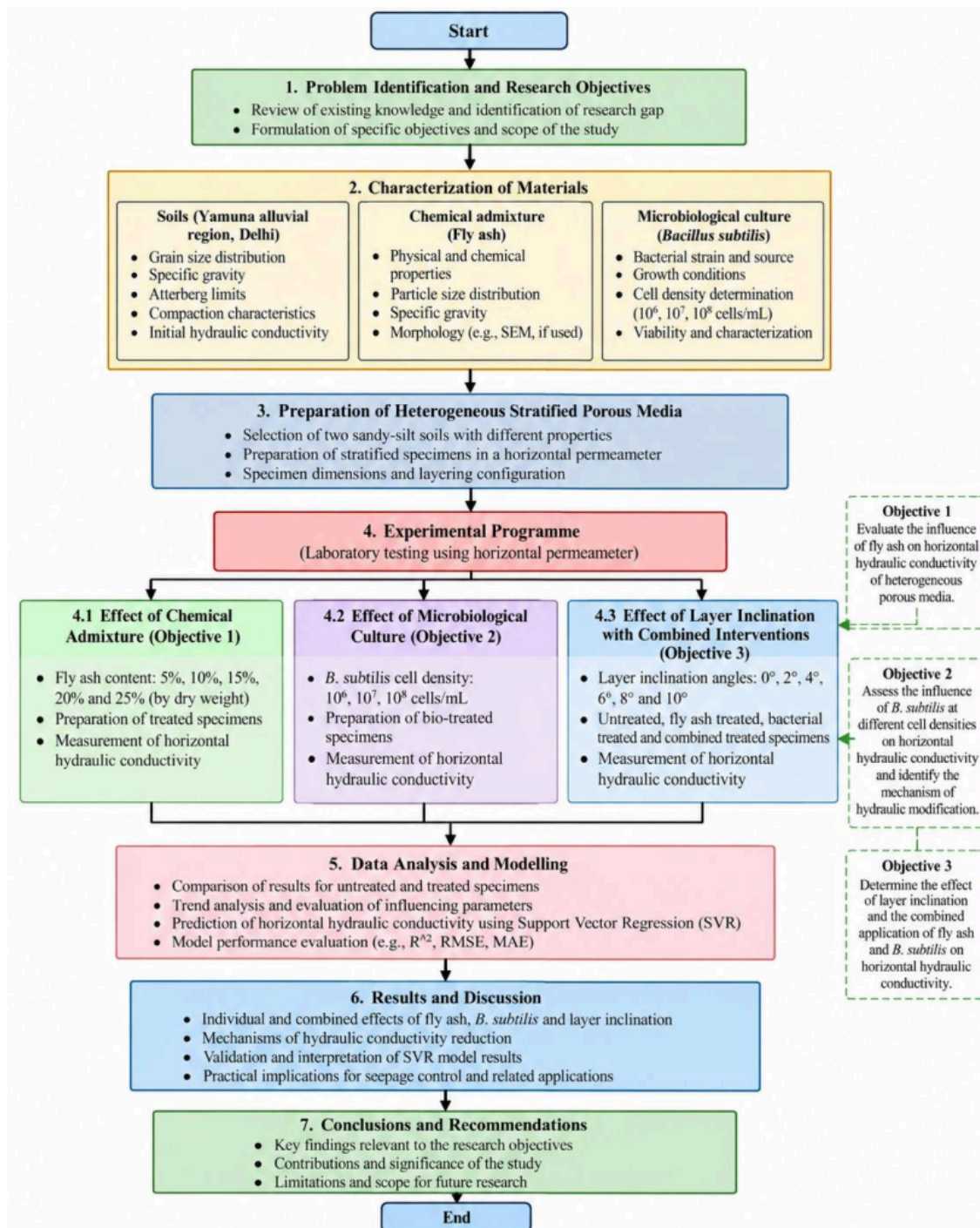


Figure 3.1 Research methodology flow chart

3.2 Experimental setup

The most often employed methodology in laboratories is the estimation of vertical permeability. The typical constant head and falling head permeability apparatus is widely utilized to furnish this information. Unlike vertical permeability testing, which follows

regulated protocols, there is currently no universally recognized method for evaluating horizontal permeability. Previous studies have employed permeameters of various shapes and sizes to determine horizontal permeability, including cuboidal and cylindrical configurations designed for specific soil types and flow conditions (Witt and Brauns 1983). A permeameter shaped as a cuboid with dimensions of 15 cm in width, 15 cm in depth, and 30 cm in height. They concluded that this particular permeameter did not exhibit any issues encountered by some devices utilized in the past (Chapuis et al. 1989). To ascertain the horizontal permeability of the material, researchers (Fwa et al. 1998) employed apparatus designed as a horizontal cylinder. A permeameter specifically designed for their needs, measuring 200 mm by 100 mm by 100 mm, was utilized to assess the permeability of geosynthetic reinforced soil in the horizontal direction (Raisinghani and Vishwanadham 2010). The radial flow apparatus was employed to test horizontal permeability (Dungca et al. 2019).

This study utilized a cuboid apparatus specifically developed to assess horizontal permeability. The complete experimental setup and principal components of the horizontal permeameter are shown in Figure 3.2. The permeameter measures 0.8 m in length, 0.5 m in width, and 0.5 m in depth, facilitating a 0.6 m long soil column for evaluating horizontal permeability. The dimensions of the permeameter were selected considering the specific requirements of the present experimental programme. The overall dimensions of $0.8 \text{ m} \times 0.5 \text{ m} \times 0.5 \text{ m}$ provide a sufficiently large testing volume compared with conventional small-scale permeability cells and accommodate a 0.6 m-long soil specimen for horizontal seepage. The 0.6 m flow length was considered adequate for establishing a measurable hydraulic gradient and allowing the seepage flow to develop through the stratified medium before reaching the outlet chamber. The width and depth of 0.5 m provide sufficient space for preparing and maintaining distinct soil layers with minimum disturbance while also reducing the relative influence of the side boundaries on the measured flow. These dimensions further permit uniform placement and compaction of the soil layers and provide adequate sample volume for investigating the influence of heterogeneity, fly-ash addition, bacterial treatment, and layer inclination. At the same time, the apparatus remains sufficiently compact to permit controlled laboratory operation and adjustment of the specimen inclination from 0° to 10° using the rotating support system. Thus, the selected dimensions represent a practical compromise between obtaining a representative heterogeneous soil volume, providing sufficient

horizontal seepage length, minimizing boundary effects, and maintaining manageable laboratory-scale operation.

The apparatus's principal construction, comprising the lateral edges of the central chamber, was constructed from 10 mm thick transparent acrylic sheets to facilitate visual observation of flow patterns and soil interaction dynamics during testing. The inlet and outflow chambers were fabricated from durable PVC to ensure structural integrity and resistance to water-induced deterioration. Fine porous screens made of stainless steel mesh with a pore size of 75 microns were installed at both sides of the central chamber to prevent dirt movement while allowing unobstructed water flow.

The complete permeameter assembly was mounted on a rigid mild-steel pedestal provided with a mechanical jacking mechanism. One end of the permeameter could be gradually raised or lowered through the jack while the opposite end acted as a supporting reference, thereby rotating the complete permeameter about the horizontal plane. This arrangement enabled the soil chamber, inlet chamber, and outlet chamber to be inclined together without disturbing the prepared stratified soil specimen. The mechanism permitted controlled adjustment of the inclination between 0° and 10° , with a minimum angular resolution of approximately 0.5° . After attaining the desired orientation, the apparatus was maintained in a fixed position during the permeability test so that the hydraulic response could be measured under a constant geometric condition.

For the present experimental programme, five inclination angles, namely 0° , 2.5° , 5° , 7.5° , and 10° , were selected. These angles provided a systematic range from the horizontal condition to a moderately inclined layered condition while maintaining sufficiently small and uniform angular increments for identifying the effect of orientation on hydraulic conductivity. The selected test angles are also the same orientation values used throughout the experimental dataset and subsequent predictive analysis.

The upper limit of 10° was adopted primarily to ensure that the experiment continued to represent predominantly horizontal seepage through the stratified medium. At relatively small inclinations, the effect of layer orientation can be investigated while the principal flow remains approximately parallel to the bedding and consistent with the horizontal hydraulic-conductivity formulation used in the study. The thesis specifically states that, even when the permeameter was inclined up to 10° , the principal flow remained aligned

with the stratified layers, supporting the applicability of the adopted equivalent horizontal hydraulic-conductivity relationship.

Inclinations greater than 10° were not included because progressively larger angles would increase the gravitational component acting along the specimen and could cause the flow response to become increasingly influenced by slope-induced hydraulic effects rather than by the intended interaction between stratification, pore structure, chemical modification, and microbial treatment. Larger inclinations could also increase the likelihood of specimen rearrangement or differential settlement within the layered soil mass, particularly during saturation and prolonged seepage. Therefore, restricting the investigation to 0° – 10° provided a practical range in which the influence of inclination could be isolated while preserving the basic horizontal-flow character of the experiment.

The input chamber, middle chamber, and output chamber constitute the three chambers positioned along the length of the permeameter. The two layers of the soil sample are placed into the central chamber of the instrument. The soil samples used in the present study were collected from Site 1, located at Delhi Technological University (DTU), Delhi, India (28.7499° N, 77.1170° E). The site is located in the alluvial plains of the Yamuna River basin and is characterized by stratified sandy silt deposits. The collected soil profile had two distinct strata: the upper 3 m of inorganic sandy silt (Layer 1) and the subsequent layer beyond 3 m, also composed of inorganic sandy silt (Layer 2). The stratified layers were employed to simulate heterogeneous porous media in the current study. The soil employed in the experiment exhibited a mean particle size (D_{50}) of 0.39 mm, determined through grain size distribution analysis, as shown in Figure 3.3. The D_{50} value corresponds to a sandy silt classification and was consistent across all analyzed samples. Six samples were collected to characterize the soil profile: three from the upper layer (Layer 1) and three from the lower layer (Layer 2).

Fly ash was selected as the chemical admixture because of its fine particle size and its potential to occupy void spaces within the soil matrix, modify pore connectivity, and increase resistance to seepage. Its addition at different percentages enables systematic evaluation of the influence of chemical modification on the horizontal hydraulic conductivity of heterogeneous stratified porous media. All materials were subjected to standard laboratory testing to determine critical geotechnical parameters, including water content, specific gravity, liquid limit, plastic limit, shrinkage limit, bulk density, dry

density, void ratio, and effective stress, with the average results for each layer presented in Table 3.1. Chemical alteration is performed in the uppermost soil layer utilizing fly ash at varying proportions of 5, 10, 15, 20, and 25 percent of the soil layer's weight. The aim is to analyze the influence of these percentages on the hydraulic conductivity of stratified porous media. The physical and chemical properties of the fly ash used in the study were determined through laboratory characterization, and the obtained values are presented in Table 3.2.

Table 3.1 Properties of soil samples

Property	Soil Layer 1	Soil Layer 2	Relevant IS Code
Colour	Brownish	Brownish	—
Soil type	Inorganic sandy silt	Inorganic sandy silt	IS 1498:1970
Water content (%)	6.35	6.78	IS 2720 (Part 2):1973
Specific gravity	2.66	2.65	IS 2720 (Part 3/Sec 1):1980
Liquid limit (%)	16.90	18.50	IS 2720 (Part 5):1985
Plastic limit (%)	8.30	12.50	IS 2720 (Part 5):1985
Shrinkage limit (%)	7.77	9.20	IS 2720 (Part 6):1972
Bulk density (g/cm ³)	1.73	1.74	IS 2720 (Part 29):1975
Dry density (g/cm ³)	1.63	1.63	IS 2720 (Part 28):1974 / Part 29:1975
Void ratio	0.64	0.63	Derived parameter

Table 3.2 Physical and chemical properties of fly ash

Constituent Property	Value	Constituent	Value(%)
Colour	Grey	Al ₂ O ₃	34.08
Percent Passing 75-micron sieve	76	Fe ₂ O ₃	2.00
Size of the particle (mm)	0.002 - 0.30	CaO	0.22
Specific gravity	2.06	MgO	0.43
Plasticity	Non-Plastic	SO ₃	0.05
		SiO ₂	59.00
		Na ₂ O	0.50
		K ₂ O	0.76
		LOI	0.63

Bacillus subtilis (MTCC 2422) was selected as the microbiological culture for the present experimental investigation. Bacillus subtilis is capable of producing extracellular polymeric substances (EPS), which can promote adhesion between soil particles and contribute to modification of the pore structure. Its microbial activity may also result in pore occupation, biofilm development, and partial clogging of interconnected flow passages. These processes can reduce the effective pore space available for water movement and thereby decrease hydraulic conductivity. The bacterium was therefore selected to investigate the effect of microbiological modification on seepage through the stratified soil system.

For cultivation, Bacillus subtilis (MTCC 2422) was grown in Tris–YE medium containing 130 mM Tris buffer adjusted to pH 9.0, 10 g/L ammonium sulphate, and 20 g/L yeast extract. The alkaline pH of 9.0 was maintained to provide a stable growth environment for the selected bacterial strain and to support microbial activity under conditions suitable for the subsequent soil-treatment experiments. The Tris buffer was used to minimize variations in pH during cultivation, since substantial changes in acidity or alkalinity may influence bacterial growth and metabolic activity. Before inoculation, the culture medium and associated laboratory materials were sterilized by autoclaving at 121°C for 15 min. This temperature–time combination was selected as a standard moist-heat sterilization condition because saturated steam at 121°C is capable of effectively inactivating vegetative microorganisms and highly resistant microbial forms, thereby reducing the possibility of contamination and ensuring that the observed response could be attributed predominantly to the introduced Bacillus subtilis culture. The 15-min

holding period provides sufficient exposure after the required sterilization temperature is reached while avoiding unnecessarily prolonged heating of the nutrient medium.

The bacterial cells were subsequently cultivated ⁵ overnight at 30°C under continuous agitation at 120 rpm. After incubation, the cells were harvested by centrifugation at 10,000 × g for 10 min, washed twice with distilled water, and finally resuspended in 100 mL of distilled water. The ⁴² bacterial concentration was quantified by measuring optical density at a wavelength of 600 nm (OD₆₀₀) using a Hitachi U-1900 spectrophotometer. Three OD₆₀₀ levels, namely 0.11, 0.45, and 0.98, were selected because they represented three clearly separated bacterial population levels corresponding approximately to 10⁶, 10⁷, and 10⁸ cells/mL, respectively, as represented in Figure 3.4. These concentrations were adopted to provide low, intermediate, and high bacterial treatment levels within the experimental programme, thereby allowing the influence of increasing microbial population on pore occupation, biofilm development, and horizontal hydraulic conductivity to be evaluated systematically. Using three distinct cell-density levels also enabled identification of whether the hydraulic response increased progressively with bacterial concentration rather than being assessed at only a single treatment level. All optical-density measurements and cell-density determinations were performed in triplicate to improve the reliability and repeatability of the experimental observations.

Water is delivered into the soil sample via the intake chamber. As it traverses the sample, it is gathered in the output chamber. A fine porous screen (75 microns) is installed at both ends of the middle chamber to prevent soil particles from entering the input chamber or escaping into the outlet chamber. This configuration guarantees that soil is confined within the central chamber. A vertical Perspex pipe with a diameter of 50 mm is put on the top of both the intake and outflow chambers for ventilation reasons. The outlet chamber contains a vertical pipe equipped with six outlet knobs, positioned 50 mm apart from center to center. When the water level in the outlet chamber ascends, it ultimately attains the outlet knobs, facilitating the discharge of surplus water into the Perspex pipe situated above the chamber. Following a designated interval, the water discharged from the outlet valves is gathered in a measuring jar. The water is subsequently expelled into the Perspex pipe ¹⁴ located on the right side of the intake chamber. The Perspex pipe on the intake side is generally situated at a greater elevation than the exit Perspex pipe on the left side.

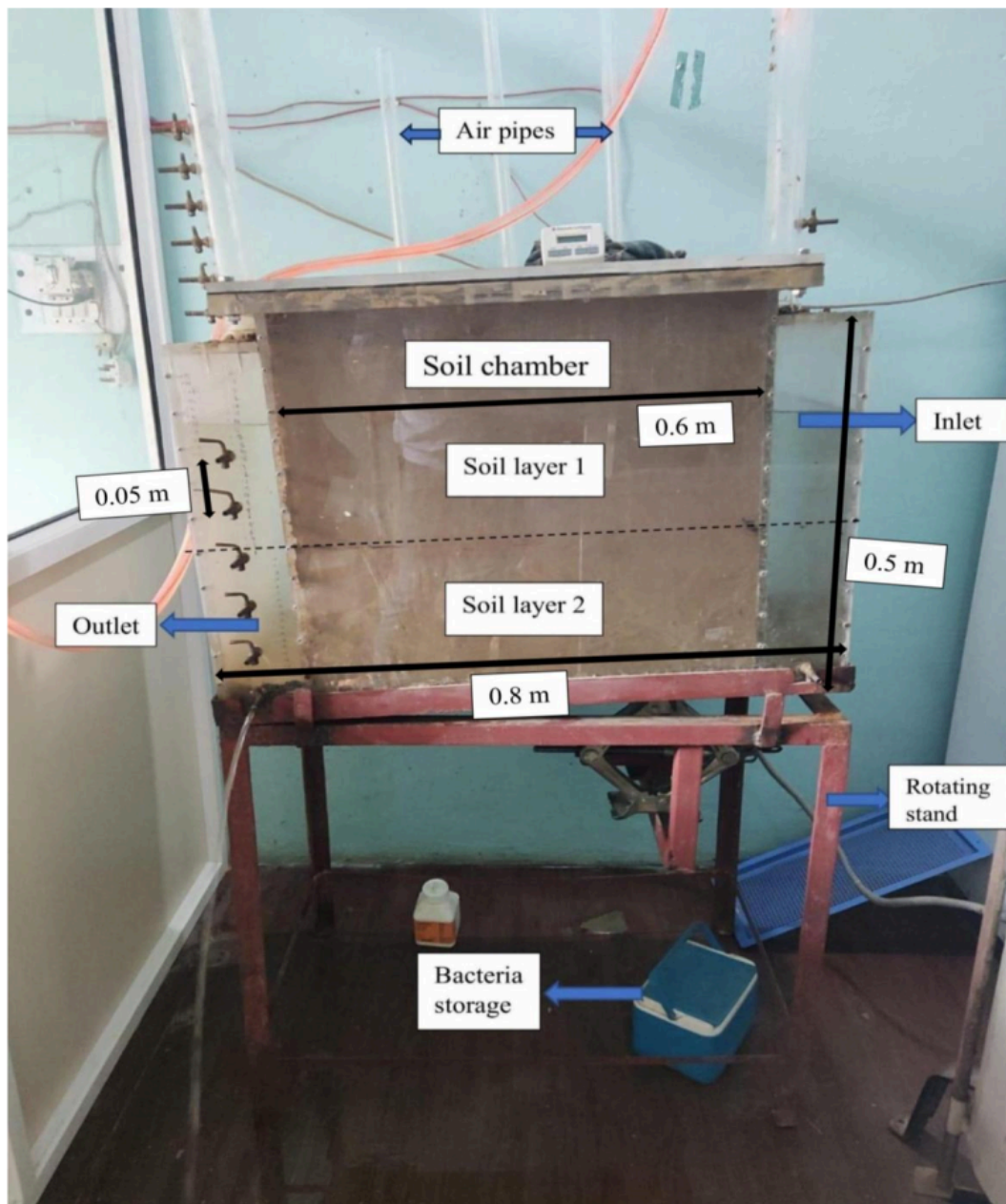


Figure 3.2 Permeameter

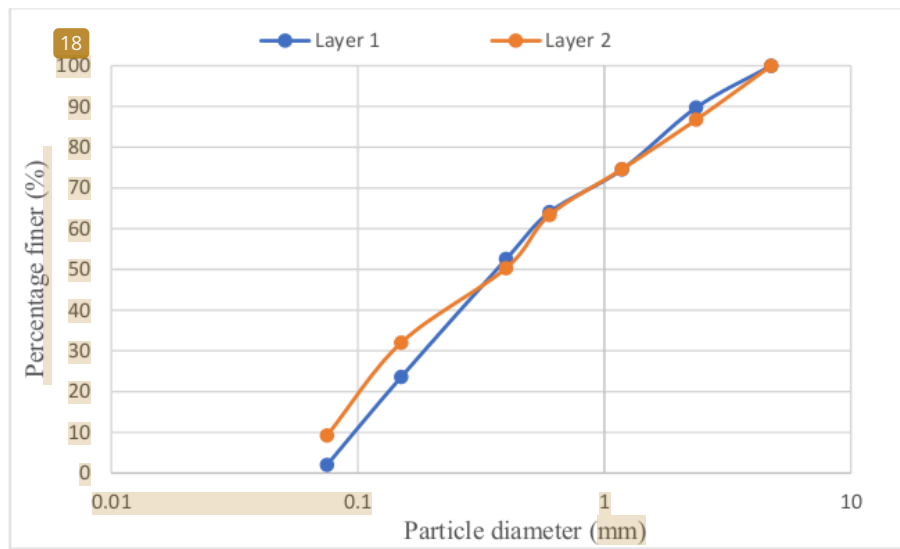


Figure 3.3 Grain size distribution of soil samples

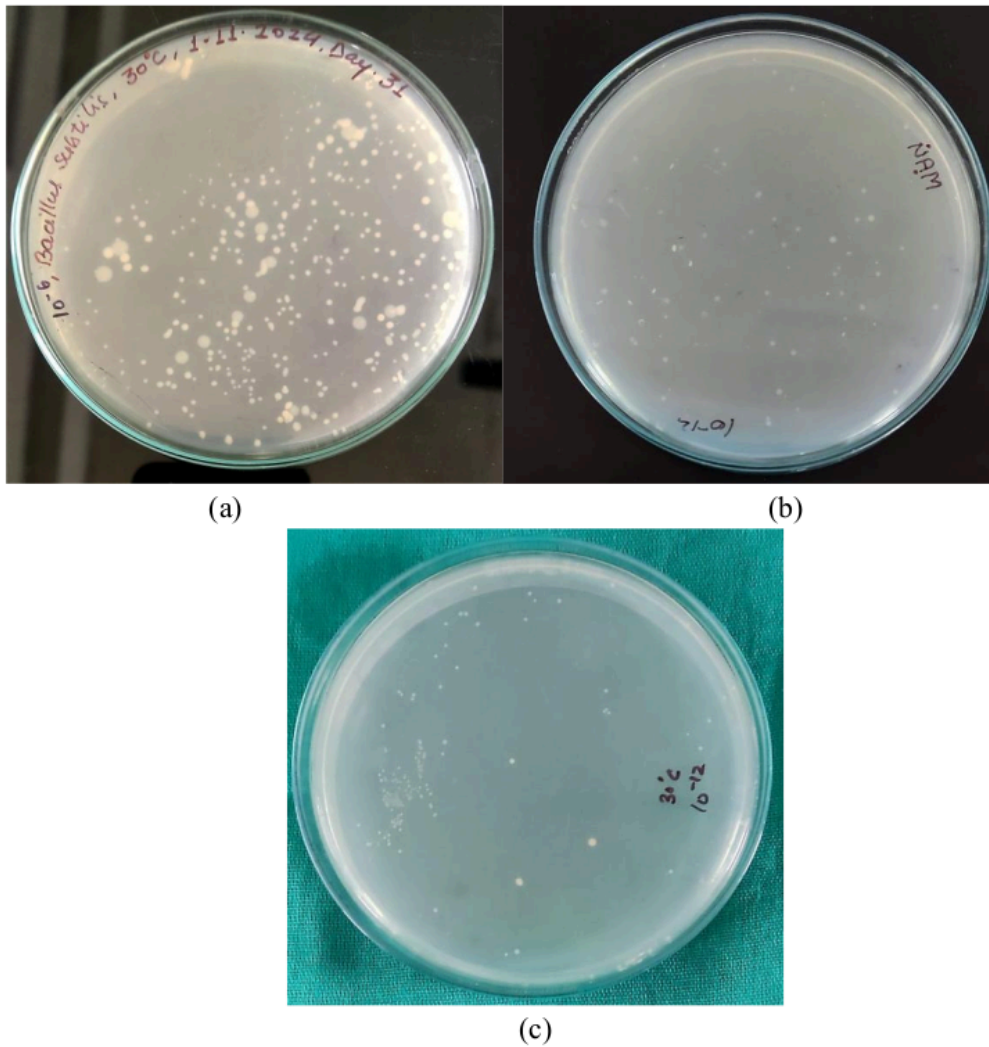


Figure 3.4 Bacterial count for different optical densities (a) 0.11, (b) 0.45, and (c) 0.98

3.3 Theoretical background

Hydraulic conductivity parallel to the bedding plane (K_h) is calculated using the equation:

$$K_h = \frac{K_1 z_1 + K_2 z_2}{z_1 + z_2} \quad (3.1)$$

Where, K_h is horizontal hydraulic conductivity, K_1 is permeability of soil layer 1, K_2 is permeability of soil layer 2, z_1 is thickness of soil layer 1 and z_2 is thickness of soil layer 2.

Equation 3.1 assumes one-dimensional horizontal flow parallel to the bedding plane, aligning with the experimental configuration employed in this study. Even with the permeameter inclined by as much as 10° , the principal flow remained consistent with the stratified layers, so validating the relevance of this idea for determining equivalent horizontal hydraulic conductivity. The hydraulic conductivity of an individual soil layer was determined using Darcy's law. Accordingly, the permeability coefficient (K) was calculated from the measured discharge (Q), flow length (l), cross-sectional area (A), and hydraulic head difference (Δh), as expressed in Equation 3.2:

$$K = \frac{Ql}{A\Delta h} \quad (3.2)$$

The study sought to investigate the impact of microbial activity and soil properties on horizontal hydraulic conductivity (K_h) in layered porous medium. The experimental matrix was formulated using essential predictor variables, including water content (w), void ratio (e), specific gravity (G), fly ash content (FC), cell density (CD), liquid limit (LL), plastic limit (PL), shrinkage limit (SL), bulk density (γ), angle of orientation (θ) (the tilt angle of the permeameter in relation to the horizontal plane), and number of layers (L). The changes were achieved by creating soil specimens with varying physical and biological characteristics under controlled laboratory conditions. Each experimental case incorporated one of three bacterial cell densities (10^6 , 10^7 , 10^8 cells/ml) and one of five orientation angles (0° , 2.5° , 5° , 7.5° , 10°) among soil samples with measured geotechnical parameters, resulting in unique data points. The experimental design facilitated a comprehensive examination of the variances in the predictor factors influencing K_h .

The input parameters are categorized into three groups: (i) Soil qualities, which include w , e , G , LL , PL , SL , and γ ; (ii) Chemical and bacterial characteristics, represented by FC and CD ; and (iii) Experimental factors, comprising θ and L . The input elements utilized

for predicting horizontal hydraulic conductivity (K_h) were chosen based on their physical significance, established relevance in previous permeability studies, and their representation of soil dynamics and bacterial influence. Parameters such as water content, void ratio, and bulk density define the physical structure of the porous medium, whereas consistency limitations offer insights into the soil's pliability and water retention properties. Specific gravity and layer count denote intrinsic soil characteristics and stratification, whereas bacterial cell density and orientation angle reflect biological and geometric influences on flow dynamics. These characteristics collectively offer a comprehensive set of effects impacting K_h in stratified porous materials. Before model training, all input variables were standardized using min-max scaling to the [0,1] range to remove bias from varying units and magnitudes, hence improving model convergence. This normalization technique was uniformly used across all machine learning models included in the study to ensure consistency and comparability. A diverse range of parameters is carefully chosen to ensure that the final model equation may be effectively applied across stratified porous media. Table 3.3 presents the details of the dataset.

The necessary equation (3.3) may be expressed as:

$$K_h = F(w, e, G, FC, CD, LL, PL, SL, \gamma, \theta, L) \quad (3.3)$$

Where w is water content, e is void ratio, G is specific gravity, FC is fly ash content, CD is cell density, LL is liquid limit, PL is plastic limit, SL is shrinkage limit, γ is bulk density, θ is angle of orientation, and L is number of layers.

Table 3.3 Statistical characteristics of dataset used

Statistics	w	e	G	FC	CD	LL	PL	SL	γ	θ	N	K_h
Range	0.43	0.01	0.30	25	1.0×10^8	4.20	1.60	1.43	0.01	10	0	0.003904
Minimum	6.35	0.63	2.36	0	0	8.30	16.90	7.77	1.73	0	2	0.000185
Maximum	6.78	0.64	2.66	25	1.0×10^8	12.50	18.50	9.20	1.74	10	2	0.004089
Average	6.57	0.64	2.51	13	3.0×10^7	10.40	17.70	8.48	1.74	5	2	0.001704
Median	6.56	0.64	2.65	13	6.0×10^6	10.40	17.70	8.48	1.73	5	2	0.001741
Standard Deviation	0.22	0.01	0.15	9	4.0×10^7	2.10	0.80	0.72	0.01	4	0	0.000972

3.4 Support Vector Regression (SVR) model

Support vector regression (SVR) is employed to validate experimental outcomes due to its superior generalization accuracy on noisy, nonlinear laboratory datasets, while mitigating the danger of overfitting. In numerous experimental studies, the correlation between input variables and the response (hydraulic conductivity) is intricate and inadequately depicted by straightforward linear equations. SVR tackles this issue by formulating an ideal regression function that optimizes the margin, often resulting in dependable predictions despite the presence of data dispersion and measurement error. Utilizing an RBF kernel, SVR may effectively encapsulate significant nonlinearity and feature interactions without necessitating an explicit physical representation of the model. Another pragmatic rationale is that SVR performs effectively with moderately big tabular datasets, whereas neural networks may exhibit sensitivity to hyperparameter selection and risk overfitting without meticulous regularization.

Furthermore, SVR operates optimally when the inputs are appropriately scaled; thus, standardization or normalization ensures stability and consistency in learning across variables with disparate units. Consequently, SVR is an excellent option for experimental validation since it offers a reliable, data-driven correlation between predictors and responses, yielding predictions that can be immediately juxtaposed with measured values to verify the consistency and reproducibility of experimental trends. SVR can utilize various kernel functions, such as polynomial, radial basis function (RBF), and sigmoid kernels, to effectively model intricate relationships among variables. Due to its adaptability, SVR has been efficiently utilized across various areas, including finance (Sharma et al. 2012), transportation (Yeh et al. 2010), and medical imaging (Borges et al. 2016). Reliable predicted performance necessitates meticulous selection of the kernel type and precise optimization of its parameters. A prevalent approach for addressing nonlinearity involves projecting the original input data x onto a higher-dimensional feature space F via a nonlinear transformation. This transformation enables the effective modeling of issues that are not linearly separable in the original space. In the altered feature space F , the decision function can be articulated as:

$$f(x) = w^T \varphi(x) + b \quad (3.4)$$

Within the feature subspace, the statistical model expressed by the algebraic function $f(x, w)$ can be written as follows:

$$w = \sum_{i=1}^n \alpha_i x_i \quad (3.5)$$

$$f(x, w) = \sum_{j=1}^n \alpha_j x_j \varphi_j(x) + b \quad (3.6)$$

$$f(x) = \sum_{i=1}^n \alpha_i x_i^T x + b \quad (3.7)$$

In the transformed feature space F, the expression can be represented as:

$$f(x) = \sum_{i=1}^n \alpha_i \varphi(x_i)^T \varphi(x) + b \quad 0 \leq \alpha_i \leq C \quad (3.8)$$

$$k(x, x') = \varphi(x)^T \varphi(x') \quad (3.9)$$

$$f(x) = \sum_{i=1}^n \alpha_i k(x, x_i) + b \quad (3.10)$$

On the other hand, a variety of additional kernel functions may also be utilized under different conditions to improve model performance.

$$\text{Linear kernel: } k(x_i, x_j) = x_i^T x_j \quad (3.11)$$

$$\text{Polynomial kernel: } k(x_i, x_j) = (\gamma x_i^T x_j + r)^d, \gamma > 0 \quad (3.12)$$

$$\text{RBF kernel: } k(x_i, x_j) = \exp(-\gamma \|x_i - x_j\|^2), \gamma > 0 \quad (3.13)$$

$$\text{Sigmoid kernel: } k(x_i, x_j) = \tanh(\gamma x_i^T x_j + r), \gamma > 0 \quad (3.14)$$

The SVM model depends on several important parameters, including C, γ , r, and d. The parameter C is the regularization or penalty parameter, which controls the trade-off between minimizing the training error and maintaining model generalization. A smaller value of C allows greater tolerance to prediction errors and generally produces a smoother regression function, whereas a larger value of C imposes a higher penalty on deviations from the training data and therefore attempts to fit the observations more closely. The parameter γ controls the influence of individual training samples in the kernel function, r represents the kernel offset term, and d denotes the degree of the polynomial kernel. This study employed SVR to predict horizontal hydraulic conductivity (K_h) because to its efficacy in learning nonlinear input-output correlations while ensuring robust generalization amongst experimental variability. The SVR model was executed utilizing the RBF kernel, commonly employed to capture intricate, non-linear interactions between soil and treatment variables without presupposing any predetermined mathematical structure.

Before training, all input features were normalized using StandardScaler to eliminate the impact of varying units and magnitudes, hence ensuring consistent convergence of the SVR model. To enhance proportional accuracy for conductivity-type data, the model was trained on a log10-transformed K_h , and the projected outputs were subsequently back-transformed to reflect K_h on the original scale. The dataset was partitioned using an 80:20 ratio (80% for training and 20% for validation) with random shuffling in MATLAB R

(2019) to guarantee representative sampling of all circumstances. The ultimate SVR hyperparameters employed for prediction were $C = 100$, γ (gamma) = 0.05, and ε (epsilon) = 0.001, utilizing the RBF kernel, where C regulates the penalty for training errors, gamma dictates the kernel width (model flexibility), and epsilon delineates the insensitive loss region surrounding the regression function. The performance of the model was assessed by contrasting predicted and observed K_h values in the validation set through standard statistical metrics, indicating that the trained SVR model can consistently replicate the experimental conductivity trend and yield precise estimates of horizontal hydraulic conductivity.

3.5 Statistical measures

A range of error analysis techniques was employed to evaluate the accuracy of the machine learning models. The selected evaluation criteria comprised the “coefficient of determination (R^2), mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), scatter index (SI), coefficient of efficiency (E), and Akaike Information Criterion (AIC).” These performance metrics are computed using the relevant equations:

$$R^2 = \frac{\sum_{i=1}^N (a_i - \bar{a})^2 (p_i - \bar{p})^2}{\sum_{i=1}^N (a_i - \bar{a})^2 \sum_{i=1}^N (p_i - \bar{p})^2} \quad (3.15)$$

$$MSE = \frac{1}{N} \sum_{i=1}^N (p_i - a_i)^2 \quad (3.16)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (p_i - a_i)^2} \quad (3.17)$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |p_i - a_i| \quad (3.18)$$

$$MAPE(\%) = \frac{1}{N} \sum_{i=1}^N \left(\frac{|p_i - a_i|}{a_i} \times 100 \right) \quad (3.19)$$

$$SI = \sqrt{\frac{\sum_{i=1}^N [(p_i - \bar{p}) - (a_i - \bar{a})]^2}{\sum_{i=1}^N a_i^2}} \quad (3.20)$$

$$E = 1 - \frac{\sum_{i=1}^N (p_i - a_i)^2}{\sum_{i=1}^N (a_i - \bar{a})^2} \quad (3.21)$$

$$AIC = N \log \left(\frac{1}{N} \sum_{i=1}^N (p_i - a_i)^2 \right) + 2k \quad (3.22)$$

Where, a is actual values, p is predicted values, $\bar{a}$ is mean of actual values, $\bar{p}$ is mean of predicted values, N is number of datasets and k is number of variables.

CHAPTER 4

RESULTS AND DISCUSSION

46

4.1 General

This chapter presents and discusses the experimental and predictive results obtained for the horizontal hydraulic conductivity of heterogeneous stratified porous media. The analysis focuses on the influence of chemical modification, microbiological treatment, and the inclination of soil layers under the different experimental conditions considered in the study. The results are interpreted in terms of changes in pore structure, flow-path continuity, and resistance to seepage within the stratified medium. The effect of fly ash content on horizontal hydraulic conductivity is first examined for different orientation angles. This is followed by an assessment of the influence of *Bacillus subtilis* at bacterial cell densities of 10^6 , 10^7 , and 10^8 cells/mL. The combined influence of fly ash and bacterial treatment is then evaluated at different layer inclinations to understand their interactive effect on hydraulic behaviour. Comparative analyses are subsequently carried out among the untreated, chemically modified, microbiologically treated, and combined-treatment conditions. In addition to the experimental interpretation, the predictive performance of the SVR model is evaluated by comparing predicted and observed values of horizontal hydraulic conductivity using the statistical measures described in Chapter 3. The discussion therefore provides an integrated assessment of the physical, chemical, microbiological, and geometrical factors governing flow through the heterogeneous porous medium and establishes the basis for the conclusions presented in the subsequent chapter.

1

4.2 Effect of chemical admixture on hydraulic conductivity of heterogeneous media

Figure 4.1 illustrates the variation in horizontal hydraulic conductivity as the orientation angle changes in 2.5° increments for fly ash contents ranging from 5% to 25% of the soil weight in the upper layer. Hydraulic conductivity increases as the orientation angle rises from 0° to 10° . A consistent trend is observed for all fly ash contents, whereas an increase in fly ash concentration at a fixed orientation results in lower horizontal hydraulic conductivity. The corresponding percentage reductions relative to the untreated condition are presented in Table 4.1. It shows that the reduction in hydraulic conductivity generally

becomes greater as the fly ash content increases, while its relative influence becomes smaller as the orientation angle increases.

Table 4.1 Percentage reduction in horizontal hydraulic conductivity due to fly ash

Orientation angle	2 5% FA	10% FA	15% FA	20% FA	25% FA
0°	10.83	27.23	40.07	56.04	65.94
2.5°	7.60	27.33	32.53	46.56	50.06
5°	5.58	20.79	28.30	34.86	38.77
7.5°	4.91	18.53	22.02	25.48	29.28
10°	6.13	16.40	19.25	22.09	24.28

The decline in horizontal permeability can be ascribed to multiple sources. A notable factor is the existence of tiny particles in fly ash. The addition of fly ash to soil, especially soil with existing fine particles, might induce a transition towards a finer particle distribution. This transition may result in heightened soil compaction and diminished pore spaces, thereby impeding water movement and decreasing permeability. The little particles in fly ash can obstruct the soil's pores, and when the concentration of fly ash escalates, the probability of these pores becoming clogged also grows. This impediment obstructs water flow in the soil, diminishing horizontal permeability. The incorporation of additional fine particles via fly ash can yield a denser soil structure, enhance cohesion and further reduce permeability due to diminished pore spaces and augmented interparticle interactions.

Furthermore, ¹³ the integration of fly ash into the soil results in enhanced soil compaction and consolidation. ¹³ The incorporation of fly ash into soil triggers various chemical processes that enhance its compaction and consolidation properties. Fly ash comprises many oxides, such as silica, alumina, and lime, which interact with the soil's inherent minerals and moisture levels. ⁴⁰ Lime in fly ash engages in a pozzolanic reaction with silica and alumina, resulting in the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). These compounds facilitate the adhesion and consolidation of soil particles, hence diminishing empty areas and augmenting the soil's overall density. As these processes progress, the soil-fly ash mixture acquires strength and stability, resulting in enhanced compaction and consolidation properties. Generally, the hydraulic

conductivity of soil escalates with an increase in slope angle, as steeper angles generate larger and more interconnected pores, hence enhancing water flow. A flat or horizontal orientation may lead to a thicker soil structure with reduced pore spaces, impeding water transport and decreasing hydraulic conductivity. Consequently, the orientation angle is vital in ascertaining the soil's capacity to transmit water.

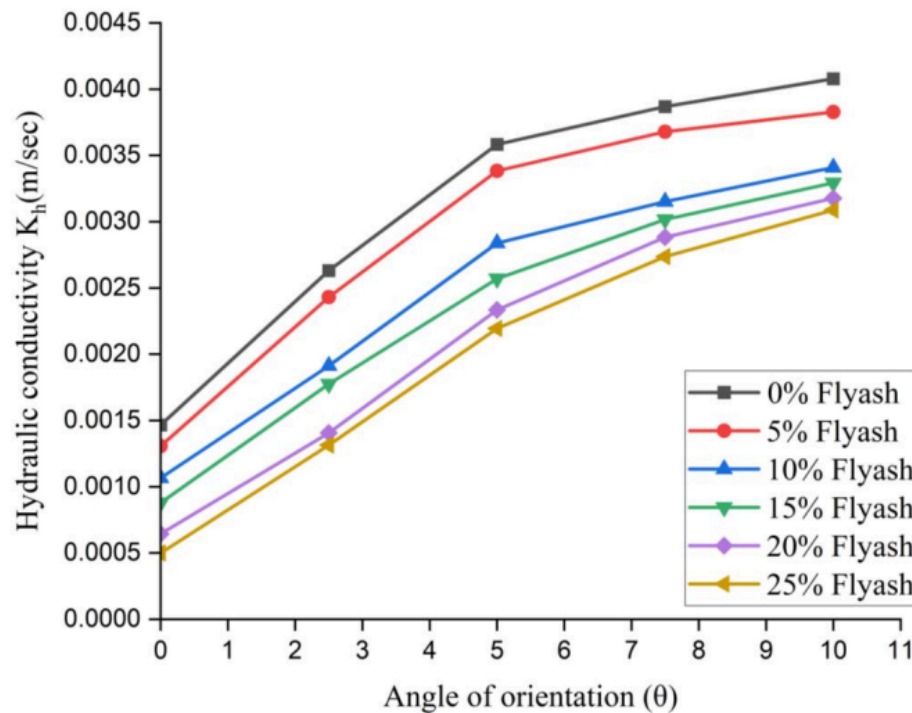


Figure 4.1 Variation of hydraulic conductivity with angle of orientation

The reduction in horizontal hydraulic conductivity observed with increasing fly ash content is consistent with the findings of Ayininuola et al. (2013), Zhou et al. (2019), and Gupta et al. (2024), as discussed in the literature review. These studies reported that mineral or chemical additives can reduce hydraulic conductivity through pore filling, densification, precipitation, and modification of pore connectivity. The present results support these mechanisms, as a progressive reduction in hydraulic conductivity was observed with increasing fly ash content. However, the present investigation extends the earlier studies by additionally considering the influence of layer inclination in a heterogeneous stratified medium. The results show that the effectiveness of fly ash in reducing hydraulic conductivity changes with layer orientation, demonstrating that chemical modification and geometrical arrangement jointly control seepage behaviour.

4.3 Effect of microbiological culture on hydraulic conductivity of heterogeneous media

Figure 4.2 illustrates the variation in horizontal hydraulic conductivity with orientation angle for different bacterial cell densities relative to the bacteria-free condition. Hydraulic conductivity increases with orientation angle in both untreated and bacteria-treated specimens. However, at every orientation the presence of bacteria lowers the conductivity, and the effect becomes more pronounced as bacterial cell density increases. The percentage reductions at the limiting orientations are summarized in Table 4.2. It indicates that bacterial treatment produces a stronger reduction at lower orientation angles and that the reduction increases as bacterial concentration rises.

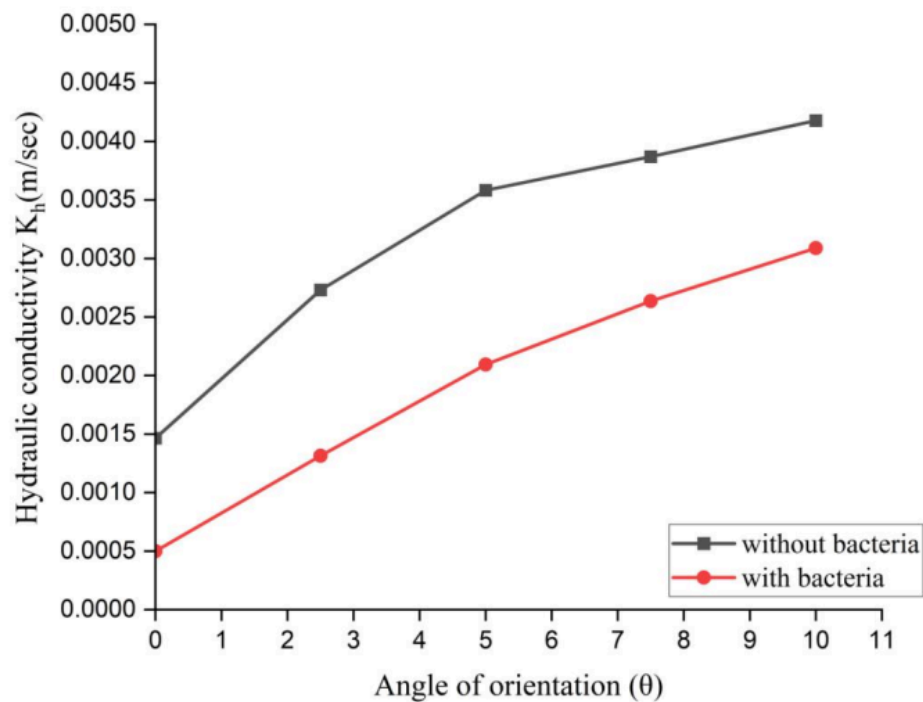
Table 4.2 Percentage reduction in horizontal hydraulic conductivity due to bacterial treatment

Bacterial cell density	Reduction at 0° (%)	Reduction at 10° (%)
10 ⁶ cells/mL	65.94	26.09
10 ⁷ cells/mL	69.01	33.65
10 ⁸ cells/mL	74.47	39.56

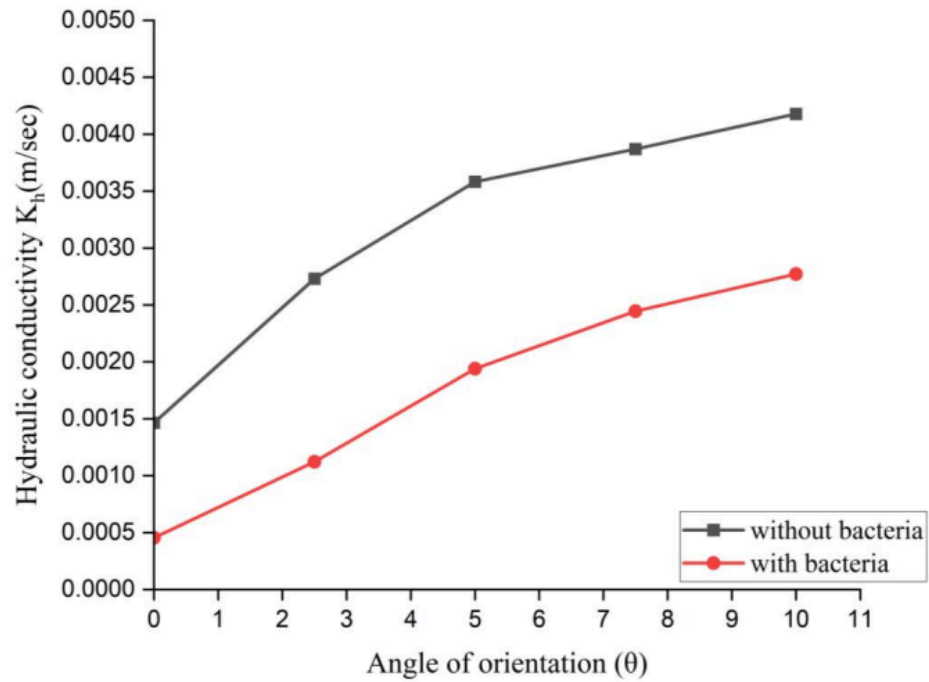
This pattern suggests that reductions in hydraulic conductivity caused by bacteria are more significant at lower orientation angles, perhaps due to the increased effectiveness of biofilm formation and pore obstruction in horizontal flow conditions. As the angle increases, fluid flow may bypass certain clogged pathways, reducing the overall impact of bacterial obstruction. The increasing trend in hydraulic conductivity concerning orientation angle is observed in all cases; nevertheless, the presence of bacteria consistently diminishes permeability, with more pronounced reductions at elevated bacterial densities. This trend highlights the crucial role of microbial activity in modifying flow dynamics inside porous media. Bacteria frequently generate biofilms, which are extracellular polymeric substances that collect on pore walls. Consequently, biofilms diminish the accessible space for fluid movement and obstruct fluid flow. The physical blockage of pore openings by bacterial cells, leading to decreased permeability, is an additional mechanism that may contribute to clogging. The effects become more severe with the increasing thickness of the biofilm and the heightened number of bacterial cells occupying the interstitial spaces as bacterial density rises. Factors contributing to the decline in hydraulic conductivity include bacterial adhesion qualities, metabolic

waste production, and the interaction between bacteria and their surrounding environment.

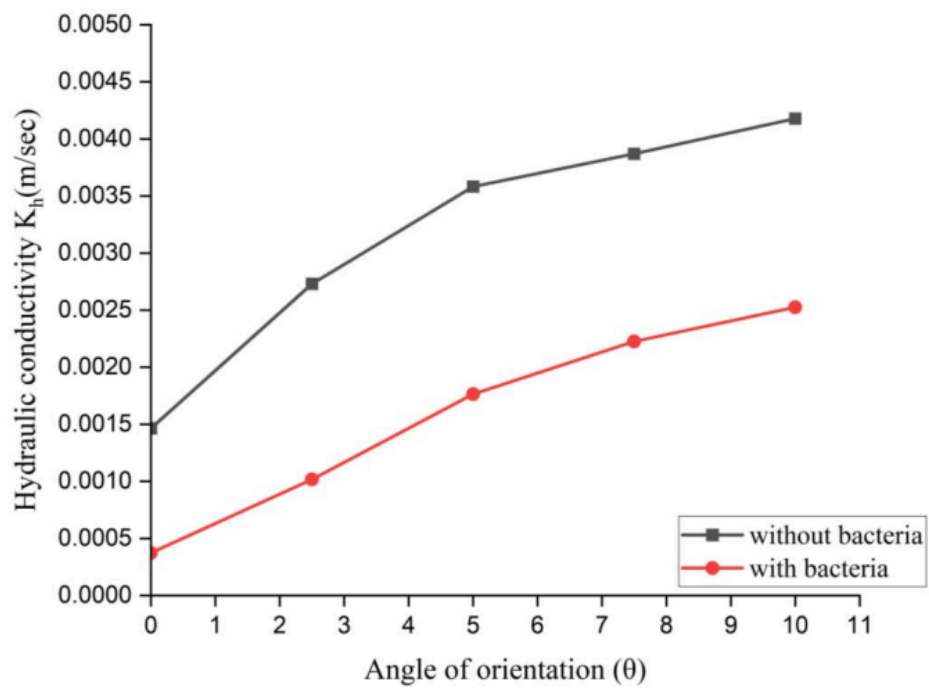
The increase in hydraulic conductivity with orientation angle suggests that flow channels become more favorable as the angle increases, either due to alterations in pore connectivity or the alignment of favored flow pathways. However, the presence of bacteria consistently impedes this function by limiting fluid flow. This inclination significantly impacts subsurface flow processes, such as groundwater remediation, oil recovery, and engineered bio barriers, where microbial activity can markedly affect permeability and fluid movement. Understanding these effects is crucial for managing bacterial growth in both natural and artificial porous media environments.



(a)



(b)



(c)

10

Figure 4.2 Variation of hydraulic conductivity with angle of orientation for different bacterial cell density (a) 10^6 cells/ml (b) 10^7 cells/ml (c) 10^8 cells/ml

36

The decrease in horizontal hydraulic conductivity with increasing *Bacillus subtilis* cell density agrees with the findings of Ivanov and Chu (2008), Brovelli et al. (2009), Umar et al. (2016), Khaleghi and Rowshanzamir (2019), and Chen et al. (2021), which were discussed in the literature review. These studies demonstrated that microbial activity can reduce porosity and hydraulic conductivity through bacterial growth, biofilm development, biomineralization, pore occupation, and bioclogging. The present study confirms these mechanisms for heterogeneous stratified media and further shows that the effectiveness of bacterial treatment is influenced by layer inclination. This provides an additional contribution because most previous microbiological studies focused on relatively simple or homogeneous porous media and did not examine microbial clogging under inclined heterogeneous conditions.

4.4 Effect of inclination of layers on hydraulic conductivity of heterogeneous porous media including chemical and microbiological interventions

Figure 4.3 illustrates the variation of horizontal hydraulic conductivity with orientation angle for stratified soil containing 5-25% fly ash at a constant bacterial cell density of 10^6 cells/mL. Conductivity increases as the orientation changes from 0° to 10° for every mixture, indicating that greater inclination promotes more favourable flow alignment and continuity. At any given angle, however, conductivity decreases as fly ash content increases in the presence of bacteria. The corresponding percentage reductions relative to untreated soil are listed in Table 4.3.

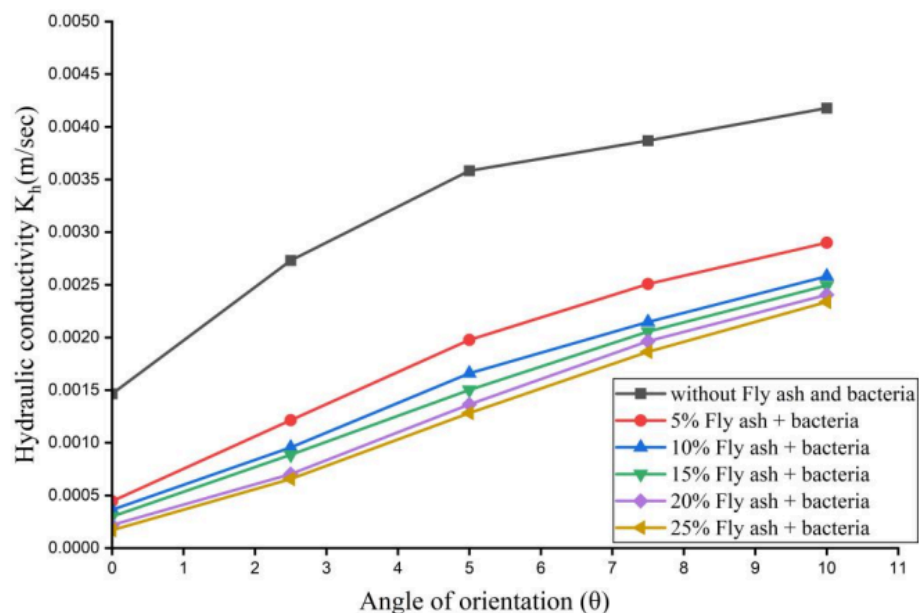
Table 4.3 Percentage reduction for fly ash combined with 10^6 cells/mL *Bacillus subtilis*

Orientation angle	5% FA	10% FA	15% FA	20% FA	25% FA
0°	69.62	75.22	79.59	85.05	88.40
2.5°	55.55	65.03	67.56	74.30	75.98
5°	44.82	53.70	58.11	61.93	64.22
7.5°	35.20	44.51	46.86	49.24	51.82
10°	30.61	38.22	40.31	42.41	44.04

The decrease in horizontal permeability with elevated fly ash–bacteria content primarily results from pore refinement and obstruction: fly ash introduces a greater quantity of fine particles that occupy voids and diminish pore-throat dimensions, while its pozzolanic

components enhance cementitious bonding, thereby densifying the matrix and reducing connectivity. Concurrently, bacterial activity can generate biofilms and stimulate mineral precipitation/bio cementation, which further occludes interconnected pores, leading to increased flow resistance as fly ash content escalates.

The increase in conductivity with orientation, despite the treated soil being less permeable than the control, is attributed to a higher angle enhancing the continuity of flow channels within the soil fabric and diminishing effective tortuosity for horizontal seepage. Thus, the percentage reduction due to fly ash–bacteria is most pronounced at 0° and progressively diminishes by 10° , as orientation partially mitigates pore-blocking by optimizing pathway alignment.



10

Figure 4.3 Variation of hydraulic conductivity with angle of orientation for different fly ash contents mixed with bacterial cell density of 10^6 cells/ml

Figure 4.4 illustrates the variation in horizontal hydraulic conductivity relative to the angle of orientation (ranging from 0° to 10° in 2.5° increments) for both untreated soil and soil modified with 5–25% fly ash, accompanied by a bacterial cell density of 10^7 cells/ml. In all instances, hydraulic conductivity rises with increasing orientation angle, demonstrating a constant angle-dependent increase, albeit at significantly lower levels in the presence of additives. The general trend of conductivity variation with angle is consistent; however, the inclusion of fly ash (with bacteria maintained at 10^7 cells/ml)

results in a distinct reduction in horizontal hydraulic conductivity at every orientation. The percentage reductions are summarized in Table 4.4.

Table 4.4 Percentage reduction for fly ash combined with 10^7 cells/mL *Bacillus subtilis*

Orientation angle	5% FA	10% FA	15% FA	20% FA	25% FA
0°	72.35	77.47	81.43	86.35	89.42
2.5°	62.03	70.16	72.28	78.03	79.49
5°	48.87	57.10	61.18	64.72	66.84
7.5°	39.93	48.54	50.74	52.93	55.34
10°	37.72	44.54	46.43	48.30	49.76

The decrease can be ascribed to the synergistic effects of pore-blocking and densification: fly ash introduces finer particles and cementitious/pozzolanic substances that occupy voids and consolidate the soil matrix, while bacterial proliferation at 10^7 cells/ml can additionally impede flow through biofilm development and microbially induced mineral precipitation, collectively diminishing interconnected pore space and consequently reducing permeability, despite the fact that an increased orientation angle still enhances effective conductivity by facilitating the continuity of flow pathways.

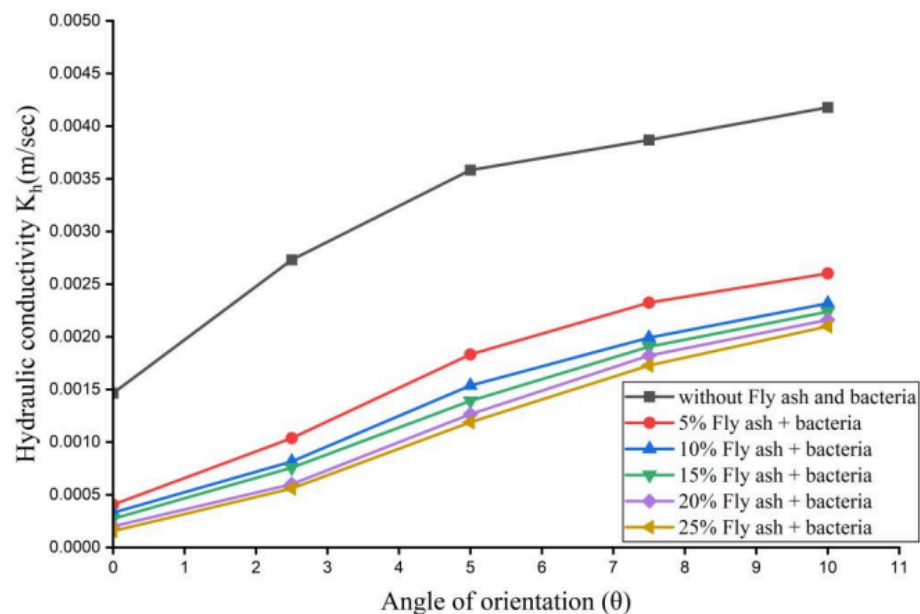


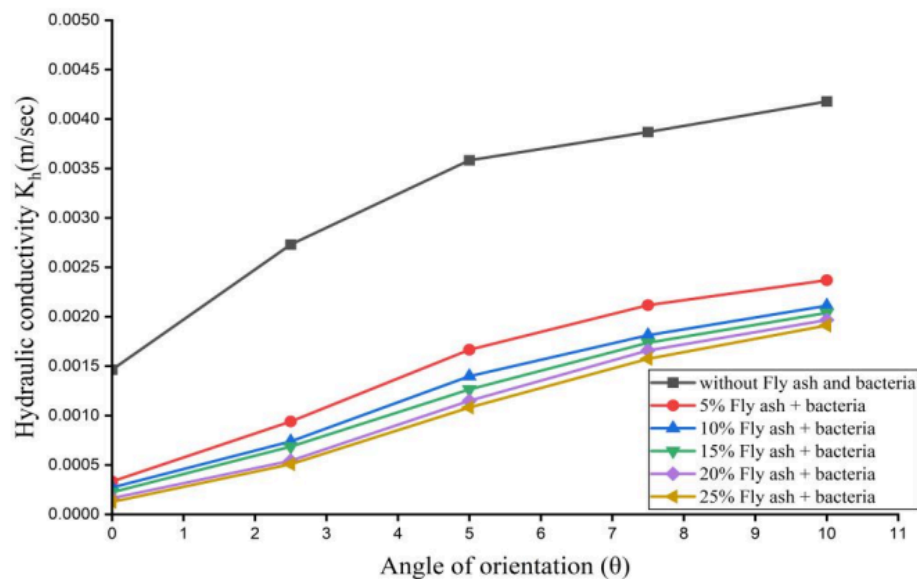
Figure 4.4 Variation of hydraulic conductivity with angle of orientation for different fly ash contents mixed with bacterial cell density of 10^7 cells/ml

Figure 4.5 illustrates the fluctuation in horizontal hydraulic conductivity (compared to the untreated soil) as a function of orientation angle for mixtures containing fly ash (5–25%) with a consistent bacterial cell density of 10^8 cells/ml across the evaluated orientations. The percentage reductions are presented in Table 4.5.

Table 4.5 Percentage reduction for fly ash combined with 10^8 cells/mL *Bacillus subtilis*

Orientation angle	5% FA	10% FA	15% FA	20% FA	25% FA
0°	77.27	81.43	84.71	88.81	91.33
2.5°	65.58	72.94	74.88	80.12	81.40
5°	53.50	60.98	64.69	67.90	69.83
7.5°	45.28	53.14	55.13	57.12	59.32
10°	43.27	49.47	51.20	52.92	54.24

The reduction in conductivity with increased fly ash dosage is primarily due to the introduction of a greater proportion of fine particles that occupy pore spaces and obstruct flow channels, resulting in a denser soil matrix with diminished interconnected voids. Furthermore, fly ash can participate in pozzolanic reactions (involving silica/alumina and available lime) that generate cementitious compounds (e.g., CSH/CAH), which agglomerate particles, compact the pore structure, and further impede water movement. Additionally, the elevated bacterial concentration (10^8 cells/ml) may exacerbate pore constriction via biological clogging mechanisms (e.g., biofilm/EPS accumulation and microbially induced precipitates), thereby diminishing effective pore throat size and connectivity. This is likely the primary reason the treated mixtures exhibit significantly lower values than the untreated scenario. The observed enhancement in conductivity with steeper orientations is linked to orientation-induced alterations in soil fabric and flow geometry, where steeper alignments facilitate larger and more interconnected flow pathways (reduced tortuosity and enhanced continuity), while flatter orientations may exhibit greater compaction and reduced connectivity, resulting in increased resistance to flow.



10

Figure 4.5 Variation of hydraulic conductivity with angle of orientation for different fly ash contents mixed with bacterial cell density of 10^8 cells/ml

The increase in hydraulic conductivity with increasing layer inclination is consistent with the earlier findings related to stratification and directional flow. Selim (1988) demonstrated the influence of inclined interfaces on two-dimensional flow through layered soils, while Stephens and Heermann (1988) reported enhanced anisotropic behaviour in stratified sands. Similarly, Burger and Belitz (1997) observed differences between horizontal and vertical hydraulic conductivity, and Sharo et al. (2021) showed that layer sequence and flow direction considerably influence equivalent permeability. The present study extends these investigations by simultaneously incorporating fly ash and microbiological modification into inclined heterogeneous porous media. Hence, the observed hydraulic response is not controlled solely by layer orientation but by the interaction among stratification, chemical pore filling, and biological obstruction.

4.5 Comparative study of hydraulic conductivity for different cases

Figure 4.6 compares horizontal hydraulic conductivity at 0° , 2.5° , 5° , 7.5° , and 10° for four conditions: control soil, fly-ash-treated soil, bacteria-treated soil at 10^6 cells/mL, and combined fly ash-bacteria treatment. The comparison is repeated for fly ash contents of 5%, 10%, 15%, 20%, and 25%. Conductivity increases with angle in all cases, while the relative reduction caused by treatment is generally greater at lower orientations and

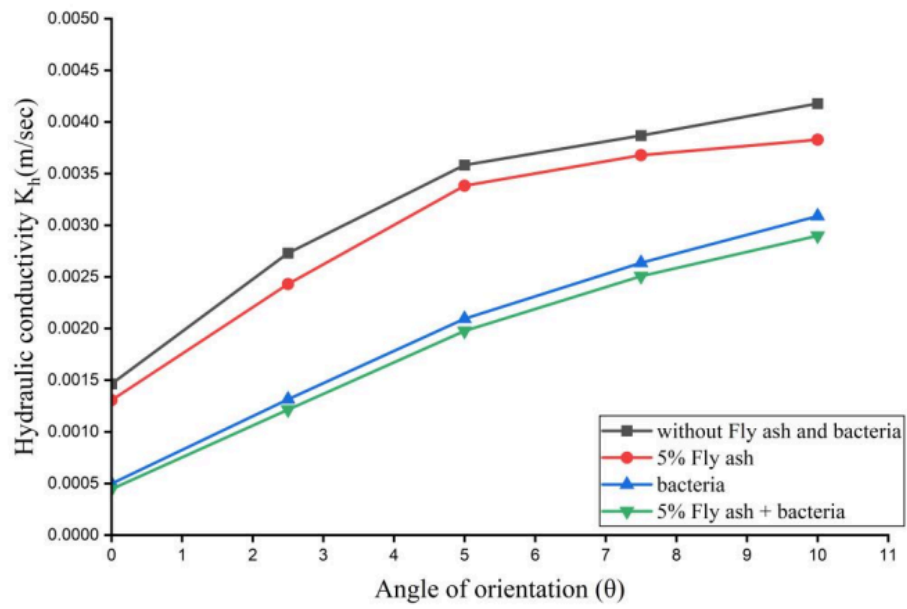
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decreases toward 10° . The percentage ranges described for the individual and combined treatments are summarized in Table 4.6.

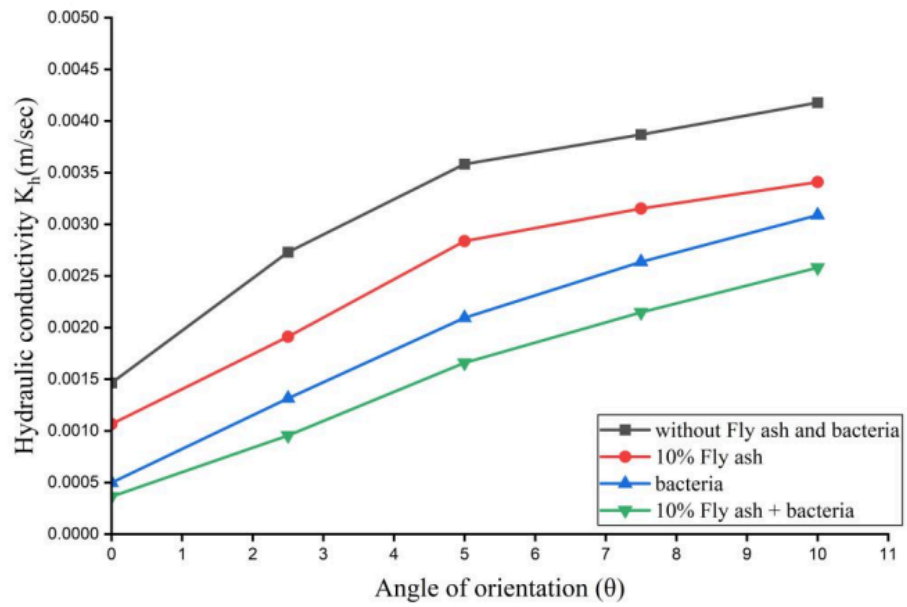
Table 4.6 Comparative percentage reduction (10^6 cells/mL)

Condition	Treatment level	Reported reduction range (%)
Fly ash only	5% FA	4.9-11.0
Fly ash only	10% FA	18.4-30.0
Fly ash only	15% FA	21.2-40.1
Fly ash only	20% FA	24.0-56.0
Fly ash only	25% FA	26.1-65.9
Bacteria only	10^6 cells/mL	26.1-65.9
Combined	5% FA + bacteria	30.6-69.6
Combined	10% FA + bacteria	38.2-75.2
Combined	15% FA + bacteria	40.3-79.6
Combined	20% FA + bacteria	42.4-85.1
Combined	25% FA + bacteria	44.0-88.4

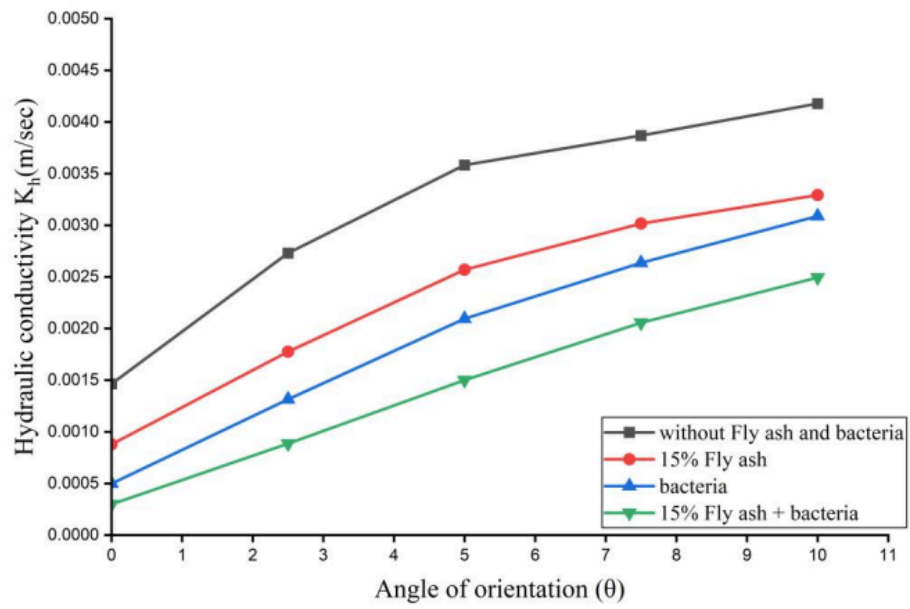
Table 4.6 demonstrates that fly ash alone lowers conductivity increasingly as its dosage rises, while the bacteria-only condition also produces a substantial reduction. The combined treatment produces the greatest decrease throughout the tested range. The mechanistic explanation remains associated with simultaneous pore modification and biological obstruction: fly ash occupies voids and improves particle packing, whereas bacterial treatment promotes pore blockage and biocementation. Acting together, these processes reduce pore connectivity more strongly than either treatment by itself.



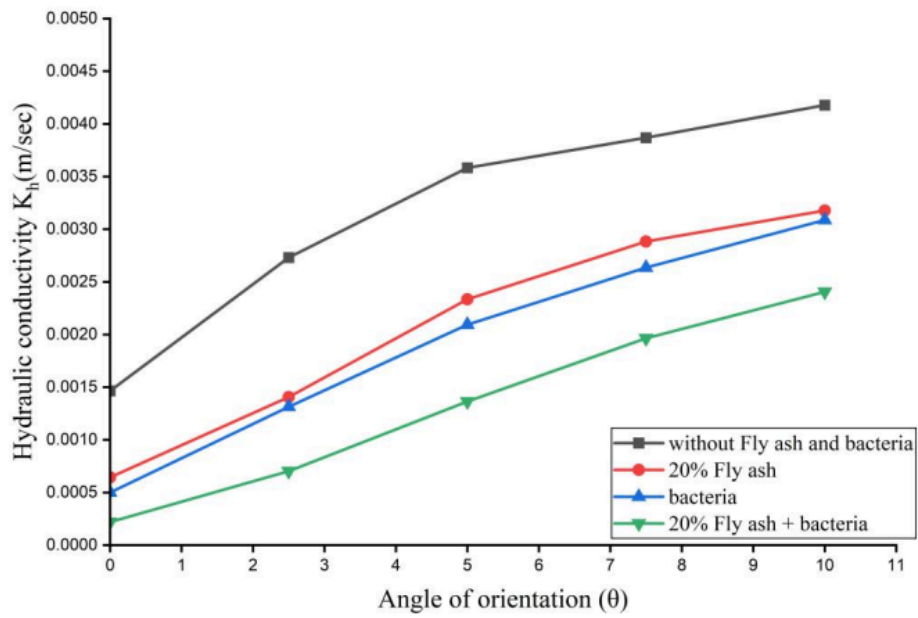
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(a)



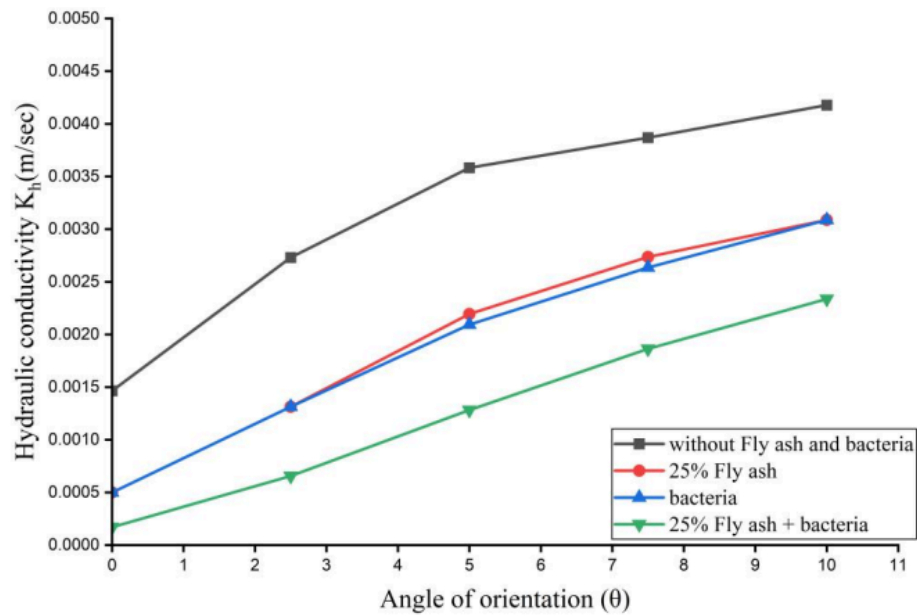
(b)



(c)



(d)



(e)

Figure 4.6 Comparative variation of hydraulic conductivity for the control specimen, fly ash, bacteria-treated specimen (cell density 10^6 cells/mL), and combined fly ash–bacteria treatments at different fly ash contents: (a) 5%, (b) 10%, (c) 15%, (d) 20% (e) 25%

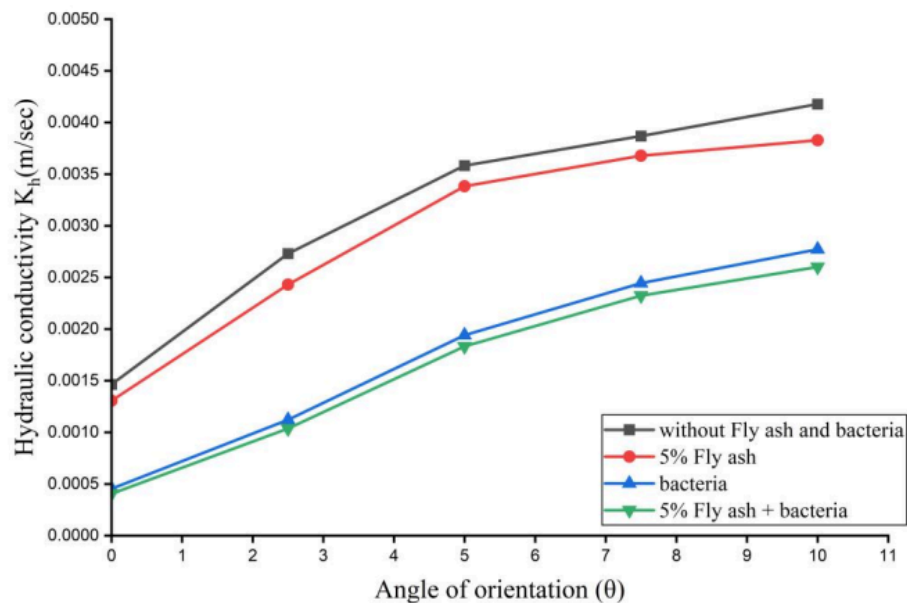
Figure 4.7 compares the same four experimental conditions using a bacterial cell density of 10^7 cells/mL. The control and treated curves all show increasing conductivity with increasing orientation angle, but treatment-induced reduction becomes less pronounced at higher angles. Fly ash alone lowers conductivity progressively with dosage, the bacteria-only condition produces a marked reduction, and the combined treatment produces the largest effect. The percentage ranges are listed in Table 4.7.

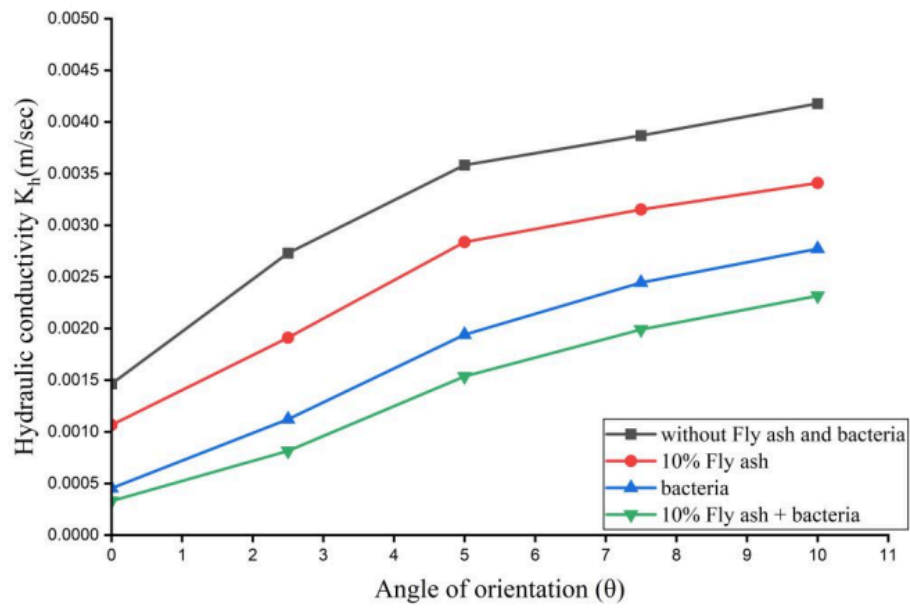
Table 4.7 Comparative percentage reduction (10^7 cells/mL)

Condition	Treatment level	Reported reduction range (%)
Fly ash only	5% FA	4.9-11.0
Fly ash only	10% FA	18.4-30.0
Fly ash only	15% FA	21.2-40.1
Fly ash only	20% FA	24.0-56.0
Fly ash only	25% FA	26.1-65.9
Bacteria only	10^7 cells/mL	33.7-69.0

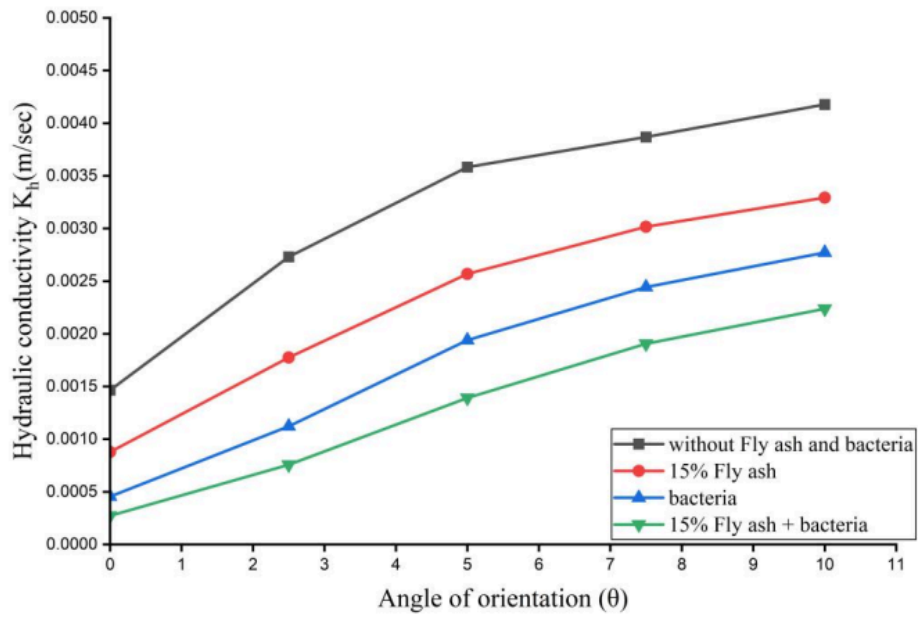
Combined	5% FA + bacteria	37.7-72.4
Combined	10% FA + bacteria	44.5-77.5
Combined	15% FA + bacteria	46.4-81.4
Combined	20% FA + bacteria	48.3-86.3
Combined	25% FA + bacteria	49.8-89.4

Table 4.7 confirms that increasing bacterial density strengthens the biological and combined effects. The systematic reduction is consistent with the original microstructural interpretation: fly ash improves packing and fills or bridges void spaces, thereby reducing pore size and connectivity; bacteria at 10^7 cells/mL intensify bioclogging and biocementation by obstructing pore throats and binding particles. When both treatments are present, the refined pore network created by fly ash can enhance the effectiveness of bacterial clogging, leading to the strongest reduction even though increasing orientation still promotes an overall rise in conductivity.

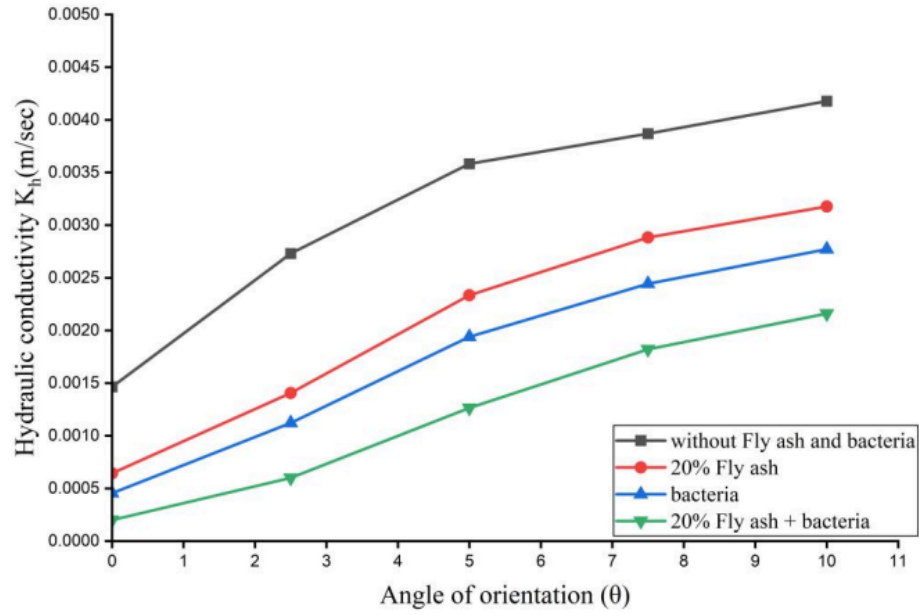




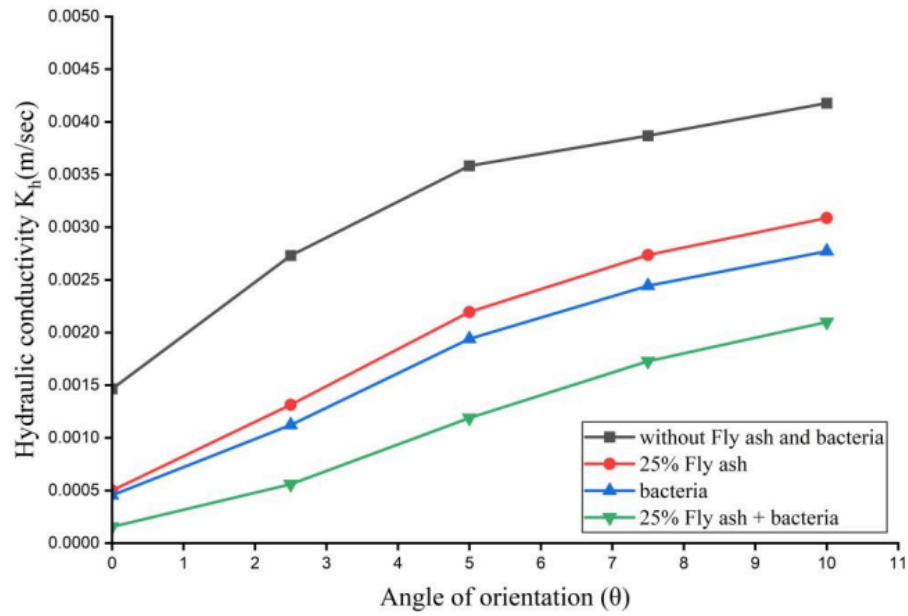
(b)



(c)



(d)



(e)

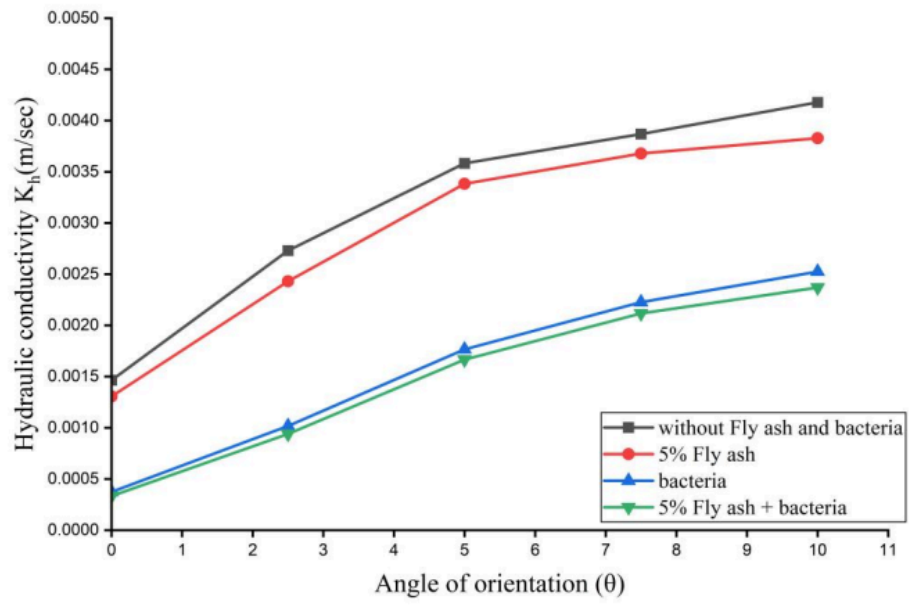
Figure 4.7 Comparative variation of hydraulic conductivity for the control specimen, fly ash, bacteria-treated specimen (cell density 10^7 cells/mL), and combined fly ash–bacteria treatments at different fly ash contents: (a) 5%, (b) 10%, (c) 15%, (d) 20% (e) 25%

Figure 4.8 compares the control specimen, fly-ash-modified soil, bacteria-treated soil at 10^8 cells/mL, and the combined fly ash-bacteria condition for the five fly ash dosages. As in the previous comparisons, all treatments reduce conductivity relative to the control, and the reduction is generally strongest at the lower angles. Increasing orientation promotes more continuous and preferential horizontal flow paths, which partly reduces the relative treatment effect. The percentage ranges are summarized in Table 4.8.

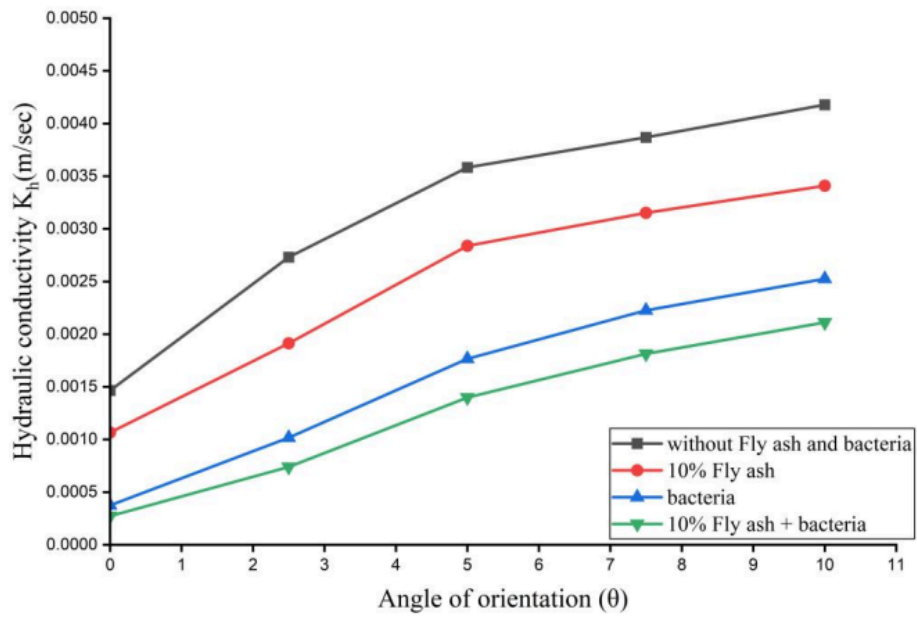
Table 4.8 Comparative percentage reduction (10^8 cells/mL)

Condition	Treatment level	Reported reduction range (%)
Fly ash only	5% FA	4.9-11.0
Fly ash only	10% FA	18.4-30.0
Fly ash only	15% FA	21.2-40.1
Fly ash only	20% FA	24.0-56.0
Fly ash only	25% FA	26.1-65.9
Bacteria only	10^8 cells/mL	39.6-74.5
Combined	5% FA + bacteria	43.3-77.3
Combined	25% FA + bacteria	54.2-91.3

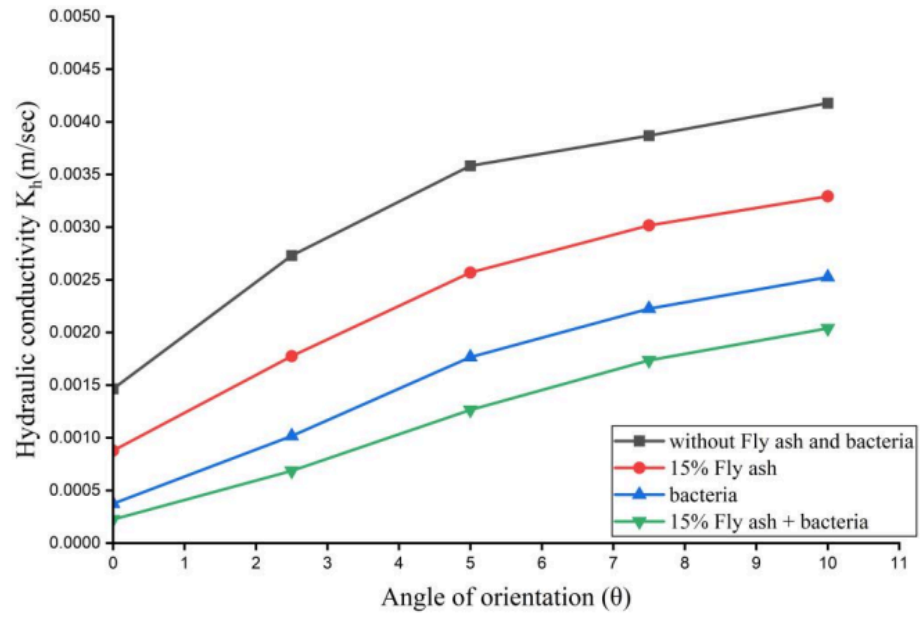
Table 4.8 shows that the high-density bacterial treatment produces a pronounced decrease, while the combined treatment yields the largest reduction. The reason remains the joint action of the two modification mechanisms. Fly ash refines and fills the pore network, whereas the high bacterial density intensifies bioclogging and biocementation. Their combined influence therefore reduces pore connectivity more strongly than either treatment alone. Although the treated specimens remain less permeable than the control, the orientation effect continues to increase conductivity by improving the continuity of preferential flow paths.



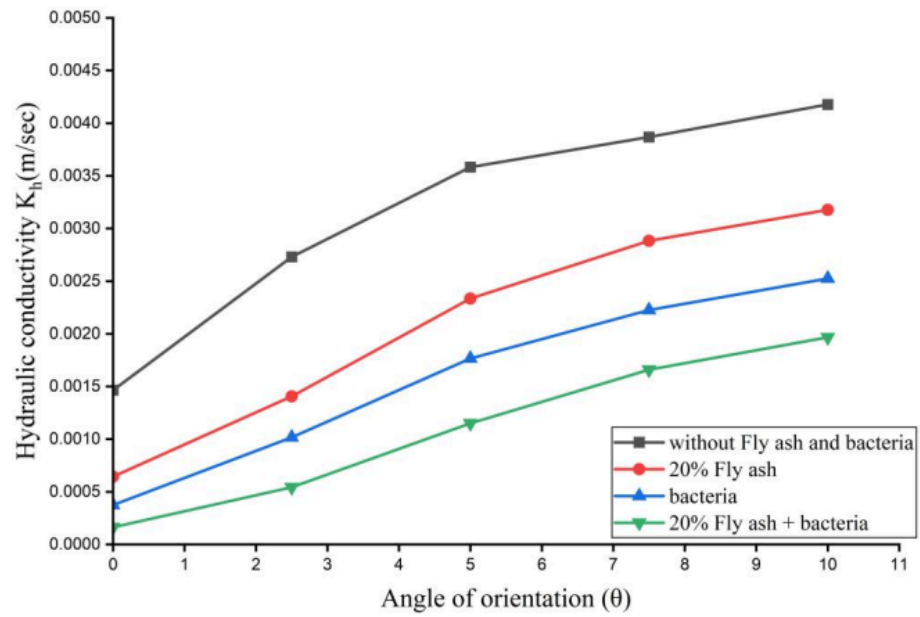
16
(a)



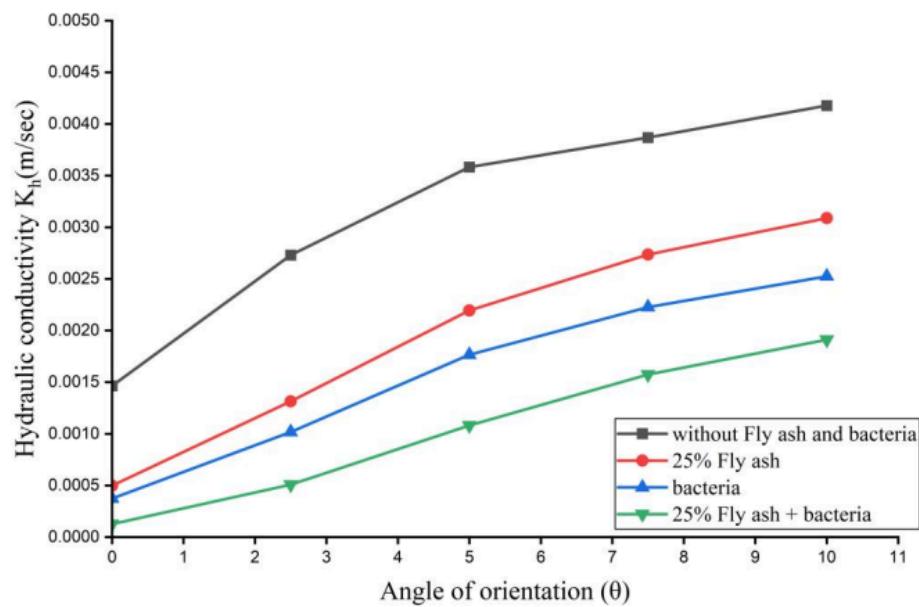
(b)



(c)



(d)



(e)

Figure 4.8 Comparative variation of hydraulic conductivity for the control specimen, fly ash, bacteria-treated specimen (cell density 10^8 cells/mL), and combined fly ash–bacteria treatments at different fly ash contents: (a) 5%, (b) 10%, (c) 15%, (d) 20% (e) 25%

Figure 4.9 compares the measured horizontal hydraulic conductivity on the x-axis with the SVR-predicted values on the y-axis for the validation dataset. The diagonal 1:1 reference line signifies perfect concordance; thus, points situated around this line suggest that the SVR model is precisely reflecting the experimental data. In this plot, the majority of points congregate near the 1:1 line, indicating that the model accurately reflects the general trend and magnitude of K_h over the spectrum of observations. Points situated above the 1:1 line represent instances of model overestimation of K_h , whilst points below the line signify underestimating. The dispersion of points around the reference line indicates the inherent variability and uncertainty in laboratory measurements and the model's approximation error; nonetheless, the lack of systematic curvature or significant bias in the scatter implies that the SVR predictions are consistent across both low and high conductivity values. The graphic demonstrates that the SVR model offers a dependable data-driven validation of the experimental conductivity results by producing predictions that closely align with the observed K_h values.

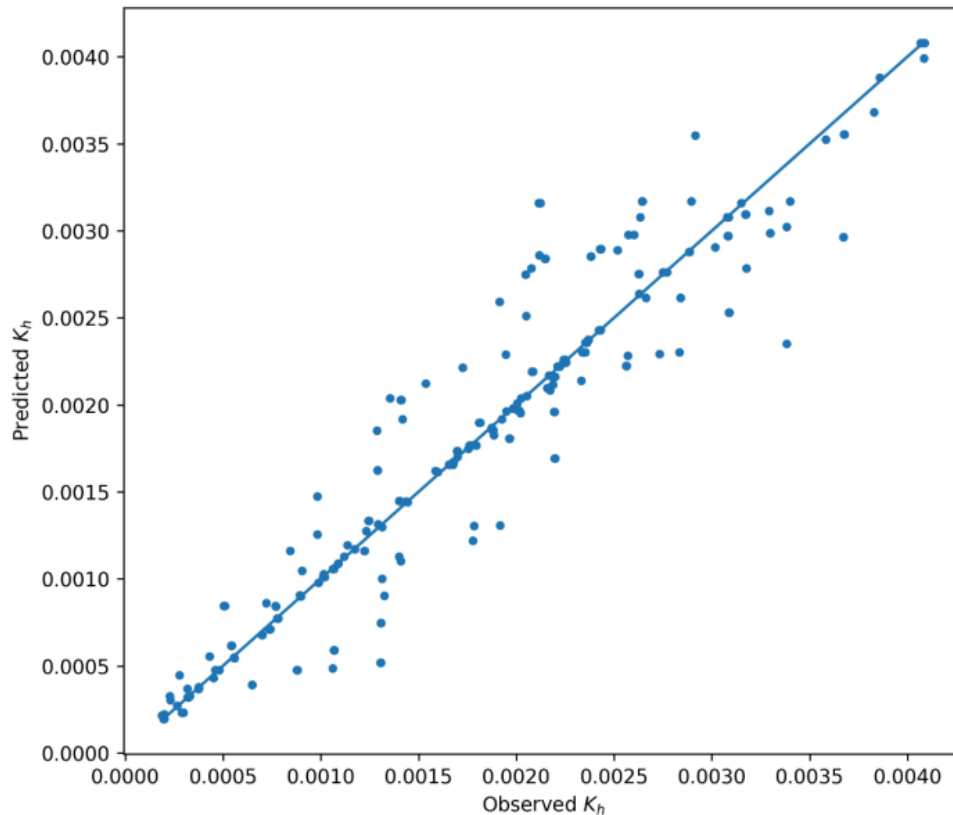


Figure 4.9 Scatter plot of observed vs predicted K_h

Table 4.9 provides a comparative statistical analysis of the anticipated horizontal hydraulic conductivity (K_h) utilizing four methodologies: the SVR model from the current study, the CART and GMDH models documented by Torabi (2022b), and the technique described by Kafi (2021). The table demonstrates that the SVR model achieves the highest concordance with experimental results, with $R^2 = 0.921$, signifying superior predictive capability and consistency compared to the other methods (CART: 0.784, GMDH: 0.849, and Kafi method: 0.905). Regarding percentage-based error, SVR exhibits the lowest MAPE at 9.81%, indicating that its predictions diverge the least from the observed K_h values when compared to CART (25.912%), GMDH (22.162%), and the Kafi technique (13.591%). Additionally, the information criterion results corroborate this conclusion: SVR exhibits the greatest negative AIC (-3850.397), indicating the optimal balance between goodness-of-fit and model adequacy among the evaluated approaches (CART: -1002.115 ; GMDH: -1246.533 ; Kafi: -2012.962). Despite variations in SI values across models (notably, the Kafi method exhibits a lower SI), the cumulative evidence from the highest R^2 and E, the lowest MAPE, and the most favourable (lowest)

AIC unequivocally demonstrates that SVR is the superior model for validating the experimental K_h results in this study, rendering it the most dependable model among those evaluated.

Table 4.9 Statistical evaluation of predicted K_h

Parameters	SVR Model	Torabi et al. (2022b) CART model	Torabi et al. (2022b) GMDH model	Kafi (2021) method
R²	0.921	0.784	0.849	0.905
MSE	9.77×10^{-8}	7.74×10^{-5}	5.18×10^{-5}	9.45×10^{-8}
RMSE	3.13×10^{-4}	8.80×10^{-3}	7.20×10^{-3}	3.07×10^{-4}
MAE	1.88×10^{-4}	5.20×10^{-3}	4.40×10^{-3}	3.87×10^{-4}
MAPE	9.81	25.912	22.162	13.591
SI	0.183	0.640	0.522	0.127
E	0.921	0.784	0.849	0.905
AIC	-3850.397	-1002.115	-1246.533	-2012.962

In comparison with previous studies, the present investigation integrates three factors that were generally studied independently: chemical modification, microbiological treatment, and layer orientation. Earlier chemical studies such as Ayininuola et al. (2013), Zhou et al. (2019), and Gupta et al. (2024) primarily focused on material modification, whereas microbial studies such as Ivanov and Chu (2008), Brovelli et al. (2009), Umar et al. (2016), Khaleghi and Rowshanzamir (2019), and Chen et al. (2021) emphasized microbial-induced changes in permeability. Stratified-media studies including Selim (1988), Stephens and Heermann (1988), Burger and Belitz (1997), and Sharo et al. (2021) mainly examined geometrical and directional effects. The present work combines these mechanisms within the same experimental framework and demonstrates that the combined fly ash–*Bacillus subtilis* treatment produces the greatest reduction in horizontal hydraulic conductivity.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Conclusions

This work demonstrates that horizontal hydraulic conductivity (K_h) in stratified porous media is significantly influenced by (i) orientation angle (0° – 10°), (ii) fly ash dosage (5–25%), and (iii) bacterial cell density (10^6 – 10^8 cells/mL). The study's findings yield a range of insights, including:

Effect of fly ash on hydraulic conductivity:

- Fly ash significantly reduced the horizontal hydraulic conductivity of heterogeneous stratified porous media. At 0° inclination, the reduction increased from 10.83% at 5% fly ash to 65.94% at 25% fly ash, showing that a higher admixture dosage produces a stronger permeability-reducing effect.
- The reduction caused by fly ash is mainly attributed to pore filling, densification of the soil matrix, and reduction in interconnected void spaces. The fine particles of fly ash increase resistance to water movement and restrict continuous seepage pathways. Thus, chemical modification using fly ash can be considered effective for controlling permeability in stratified porous media.

Effect of microbiological treatment:

- The application of *Bacillus subtilis* produced a marked reduction in horizontal hydraulic conductivity, and the effect increased with bacterial cell density. At 0° inclination, the reduction reached approximately 65.94%, 69.01%, and 74.47% for bacterial concentrations of 10^6 , 10^7 , and 10^8 cells/mL, respectively.
- The decrease produced by bacterial treatment is associated with pore occupation, extracellular polymeric substance formation, biofilm development, and bioclogging. These processes reduce the effective pore space and obstruct flow channels, thereby increasing resistance to seepage.

Effect of layer inclination:

- Horizontal hydraulic conductivity generally increased as the inclination of the stratified layers increased from 0° to 10° . This indicates that layer orientation alters the continuity and geometry of preferential flow paths. The influence of both fly ash and bacterial treatment became comparatively smaller at higher inclinations, showing that geometrical arrangement plays an important role in controlling the overall hydraulic response.

Combined effect of fly ash and *Bacillus subtilis*:

- The combined treatment produced a substantially greater reduction in hydraulic conductivity than either fly ash or bacterial treatment used independently. This demonstrates the complementary action of physical pore filling by fly ash and biological pore obstruction by bacterial activity.
- The most effective condition within the investigated experimental range was obtained with 25% fly ash and 10^8 cells/mL *Bacillus subtilis* at 0° inclination, where horizontal hydraulic conductivity decreased by approximately 91.33% relative to the untreated condition. This represents the optimum treatment condition identified in the study.
- The effectiveness of the combined treatment decreased with increasing layer inclination. This suggests that the proposed chemical–microbiological treatment is likely to be more effective for low-to-moderately inclined stratified deposits, where pore-filling and bioclogging mechanisms can act more efficiently.
- The comparative results establish that hydraulic conductivity in heterogeneous porous media is not governed by a single factor. Instead, it is controlled by the combined interaction of material composition, microbial activity, treatment intensity, and layer orientation.
- The Support Vector Regression model successfully captured the nonlinear variation in horizontal hydraulic conductivity. The model achieved $R^2 = 0.921$, MAPE = 9.81%, and AIC = -3850.397, demonstrating satisfactory predictive performance for the experimental dataset.
- The findings demonstrate that controlled chemical and microbiological modification can provide an effective approach for reducing seepage through heterogeneous stratified soils. The results have potential relevance to seepage-control systems,

engineered liners, ground improvement, waste-containment facilities, and groundwater-protection applications.

Overall, all research objectives were achieved by quantifying the individual and combined effects of fly ash, *Bacillus subtilis*, and layer inclination on horizontal hydraulic conductivity and by identifying the mechanisms responsible for the observed hydraulic response.

5.2 Future scope of work

The potential expansion of this study could involve:

- Augment the investigation utilizing SEM/EDS, XRD, and FTIR to quantitatively assess alterations in pore-size distribution, pore connectivity, and cementitious/biomineral products, thereby correlating the observed reductions in K_h with quantifiable microstructural causes.
- Perform aging and durability assessments in authentic environmental cycles to evaluate the stability of biofilm/bio cement and fly ash interactions, and to ascertain whether the reduction in permeability is sustained over time.
- Evaluate alternative microorganisms (and mixed cultures) and juxtapose them with *Bacillus subtilis*.
- Investigate various binders incorporating fly ash (such as GGBS, lime, and cement) to identify the optimal mix.

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PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15

PAGE 16

PAGE 17

PAGE 18

PAGE 19

PAGE 20

PAGE 21

PAGE 22

PAGE 23

PAGE 24

PAGE 25

PAGE 26

PAGE 27

PAGE 28

PAGE 29

PAGE 30

PAGE 31

PAGE 32

PAGE 33

PAGE 34

PAGE 35

PAGE 36

PAGE 37

PAGE 38

PAGE 39

PAGE 40

PAGE 41

PAGE 42

PAGE 43

PAGE 44

PAGE 45

PAGE 46

PAGE 47

PAGE 48

PAGE 49

PAGE 50

PAGE 51

PAGE 52

PAGE 53

PAGE 54

PAGE 55

PAGE 56

PAGE 57

PAGE 58

PAGE 59

PAGE 60

PAGE 61

PAGE 62

PAGE 63

PAGE 64

PAGE 65

PAGE 66

PAGE 67

PAGE 68

PAGE 69

PAGE 70

PAGE 71

PAGE 72

PAGE 73

PAGE 74

PAGE 75

PAGE 76
