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Research Status and Advances in Improvement Techniques for Dispersive Soil

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Abstract: ***As a special type of clay soil with strong water sensitivity, dispersive soil poses a significant threat to the stability of water conservancy, transportation, and other infrastructure due to its tendency to disintegrate upon wetting and its weak erosion resistance. This paper systematically reviews the discovery history, distribution characteristics, and engineering hazards of dispersive soil worldwide, with a particular focus on summarizing research progress regarding its dispersion mechanisms, identification methods, and improvement techniques. The review indicates that the dispersivity primarily stems from high exchangeable sodium ion content and an alkaline environment, which increase inter-particle repulsive forces. Its identification requires a combination of various laboratory tests and field investigations. Regarding improvement techniques, current research has expanded from traditional methods such as chemical cation exchange (e.g., using aluminum or calcium salts) and solidification with pozzolanic materials (e.g., fly ash, slag), to the use of organic amendments like lignosulfonates, and environmentally friendly biotechnologies such as Microbially/Enzyme Induced Calcium Carbonate Precipitation (MICP/EICP). Future research should focus on developing efficient, low-cost, and ecologically sustainable improvement technologies, while strengthening the long-term stability assessment of these improvements under complex environmental conditions (e.g., freeze-thaw cycles).***

Keywords: Dispersive Soil, Dispersion Mechanism, Soil Improvement, Environmentally Friendly Materials.

1. Introduction

Dispersive soil represents a distinct and challenging category within the geotechnical domain, characterized by its propensity to deflocculate and erode under the influence of even modest seepage forces. This behavior stems from a fundamental electrochemical imbalance: the electrostatic repulsive forces between clay particles surpass the attractive van der Waals forces, leading to individual particle detachment in the presence of water [1]. These soils are not a geological rarity; they are found across all continents, with a pronounced prevalence in arid and semi-arid regions where specific climatic and geochemical conditions favor their formation. The engineering significance of dispersive soils is profound, as they pose severe and often insidious threats to the integrity of water-retaining structures, embankments, road subgrades, and other earthworks.

The recognition of dispersive soils as a specific geotechnical hazard can be traced to the mid-20th century, following a series of perplexing and catastrophic dam failures. The 1930s marked the initial scientific identification of self-dispersing soils, but it was the 1949 failure of the Wister Dam in Oklahoma, USA, that crystallized the issue within the engineering community. A. Casagrande's seminal investigation attributed the failure to piping initiated through highly dispersive clay core material, establishing a direct link between soil dispersivity and catastrophic infrastructure collapse [2]. Subsequent decades revealed a global pattern. In Australia, studies by Cole and Lewis indicated that over 10% of earth dam incidents were linked to dispersive soils. Similarly, the failure of the San Juan Reservoir dam in Spain was later diagnosed as a consequence of using dispersive clays in its construction [3,4]. China's encounter with this issue, while somewhat later, followed a similar trajectory. Early research was catalyzed by major national projects, such as the investigation into foundation soils for the Xiaolangdi Dam on the Yellow River. Later, regional infrastructure development, particularly in Northeast China (e.g., the "Yin-Nen-Ru-Bai" water diversion project in western Jilin's saline-alkali lands), brought widespread dispersive soil problems to the fore, underscored by domestic failures like the 1995 breach of the Lingluo Reservoir in Hainan [5].

These historical incidents underscore a critical reality: conventional geotechnical analyses, which rely on standard index properties and shear strength parameters, are inadequate for identifying dispersive soils, as their physical and mechanical behavior can appear identical to that of non-dispersive clays. This disguise makes them a "hidden defect" in construction materials. Consequently, the development of reliable identification protocols and effective, sustainable improvement strategies has become a central focus of geotechnical research. This paper aims to provide a comprehensive review of the current state of knowledge on dispersive soils. It will systematically examine their complex dispersion mechanisms, critically evaluate the suite of available identification and assessment methodologies, and synthesize the principles, applications, and efficacy of the evolving spectrum of improvement techniques. By doing so, it seeks to offer a consolidated reference to inform both ongoing theoretical inquiry and practical engineering decision-making in dealing with this complex geomaterial.

2. Identification and Assessment of Dispersive Soils

Accurate identification is the critical first step in managing the risk posed by dispersive soils. Given their deceptive similarity to stable clays in terms of Atterberg limits, compaction characteristics, and standard strength tests, specialized diagnostic procedures are essential. The current paradigm relies on a combination of laboratory dispersion tests and careful engineering geological assessment of the site, including mineralogical analysis (e.g., presence of smectite) and environmental history (e.g., sodium-rich groundwater).

The most commonly employed laboratory tests form a toolkit, each probing a different aspect of dispersive behavior:

The Crumb Test: A simple, quick screening tool where a small soil pat is immersed in water. Dispersive soils typically show a cloud of colloids emanating from the pat. However, its qualitative nature makes it highly subjective, influenced by operator experience, and prone to false negatives/positives, especially in soils of intermediate dispersivity [6].

The Pinhole Test: This test simulates concentrated seepage by forcing water through a small (1.0 mm) hole in a compacted soil specimen. It directly assesses erosion resistance and classifies soils based on the turbidity of effluent and the final size of the pinhole. While considered one of the most reliable indicators, it can erroneously classify highly sensitive clays or very erodible silts as dispersive, as their failure mechanism is mechanical rather than electrochemical [7,8].

The Double Hydrometer Test: Also known as the soil dispersion ratio test, it compares the amount of clay-sized material dispersed in pure water versus a chemical dispersant. A high ratio suggests natural dispersivity. Its limitation is that it measures only the tendency to deflocculate, not the actual erosion rate under flow [6].

Chemical Tests: These include the Pore Water Soluble Cation Test, which analyzes the relative concentrations of sodium (Na^+) to divalent cations (Ca^{2+}, Mg^{2+}) in the soil's pore water, and the Exchangeable Sodium Percentage (ESP) test, which measures the proportion of sodium ions on the soil's exchange complex. High values (e.g., ESP > 10-15%) are strong indicators of dispersivity. However, results can be sensitive to sample preparation, dilution, and testing conditions, introducing uncertainty [9].

No single test is universally conclusive. Current best practice mandates a "weight-of-evidence" approach, integrating results from at least two or three of these tests (commonly Pinhole, Crumb, and ESP) alongside field observations. This multi-pronged strategy significantly enhances diagnostic reliability. Furthermore, research is increasingly focusing on context-specific factors. For instance, in seasonally frozen regions like Northeast China, studies have investigated how cyclic freezing and thawing can alter fabric and pore structure, potentially exacerbating the dispersive potential or influencing the long-term performance of improved soils, adding a vital layer to the assessment framework for cold-regions engineering [10,11].

3. Research Progress on Dispersive Soil Improvement Techniques

The overarching goal of all improvement techniques is to counteract the mechanisms causing dispersion: either by modifying the pore fluid chemistry to suppress double-layer repulsion, or by creating new bonds to "lock" particles together against erosive forces. Modern research has diversified well beyond traditional lime stabilization, exploring a range of chemical, industrial by-product, organic, and biological agents.

3.1 Chemical Replacement/Stabilization Method

This classic approach is grounded in soil chemistry principles. It involves amending the soil with salts containing polyvalent cations (Ca^{2+}, Mg^{2+}, Al^{3+}). These ions exchange with the monovalent Na^+ ions adsorbed on clay particle surfaces. According to the Gouy-Chapman double-layer theory, this exchange compresses the diffuse double layer, thins the hydrated film, and reduces the net interparticle repulsion, promoting flocculation and aggregation.

Research has explored various agents: Magnesium chloride offers a source of Mg^{2+} [12]. Alum ($Al_2(SO_4)_3 \cdot 18H_2O$) and hydroxy-aluminum solutions provide highly charged Al^{3+} ions, which are particularly effective due to their high charge density [13-16]. Polyaluminum chloride (PAC), a pre-hydrolyzed form of aluminum, introduces both Al^{3+} for exchange and polymeric Al species that can form bridges between particles, enhancing flocculation and strength simultaneously [17]. Innovative approaches like using biomimetic karst calcium bicarbonate generate Ca^{2+} ions in situ through dissolution/precipitation cycles, offering a more controlled chemical delivery [18].

3.2 Pozzolanic Material Solidification Method

This sustainable method leverages industrial by-products or wastes, turning an environmental liability into a geotechnical asset. Materials like fly ash (Classes C and F), calcined coal gangue, ground granulated blast furnace slag (GGBFS), steel slag, calcium carbide slag, and recycled concrete powder are rich in silica (SiO_2) and alumina (Al_2O_3). In the presence of moisture and an activator (often calcium from the soil or added lime), these amorphous phases undergo pozzolanic reactions, forming cementitious compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) [19-23].

These gels bind soil particles together at the micro-scale, effectively "gluing" the fabric and filling pore spaces. This process not only dramatically reduces dispersivity by creating a cohesive matrix but also significantly improves compressive and shear strength. Studies on GGBFS and steel slag have shown their dual role in suppressing dispersion and enhancing mechanical properties [24-26]. The use of carbide slag (rich in $Ca(OH)_2$) and recycled concrete powder (containing residual cement hydrates) further exemplifies the principle of circular economy in ground improvement [27].

3.3 Organic Amendment Method

This category uses organic polymers or derivatives to modify soil behavior. Lignosulfonates, a by-product of the paper industry, are the most studied. Their mechanism is multifaceted: (i) they hydrolyze to release polyvalent cations (Ca^{2+}, Mg^{2+}) for ion exchange; (ii) their large anionic polymer chains adsorb onto the positively charged edges of clay particles (at appropriate pH), acting as a bridge; and (iii) upon drying, they form a tough, water-resistant coating that binds particles [28-30]. Research by Vakili et al. and others has shown that combining lignosulfonates with polypropylene fibers creates a hybrid reinforcement system, where fibers provide tensile resistance against crack development and the lignosulfonate stabilizes the clay matrix, yielding superior technical performance and cost-effectiveness [31,32].

Another promising biopolymer is xanthan gum. Even at low doses (e.g., 0.5-1.0% by weight), it can dramatically increase viscosity and erosion resistance by forming a hydrogel network that connects soil particles through hydrogen bonding [33,34].

3.4 Biological Improvement Method

Biogeotechnical approaches, primarily Microbially Induced Calcium Carbonate Precipitation (MICP) and Enzyme Induced Calcium Carbonate Precipitation (EICP), represent a paradigm shift towards eco-friendly improvement. MICP employs urea-hydrolyzing bacteria (e.g., Sporosarcina pasteurii), while EICP uses plant-derived urease enzyme. Both catalyze the hydrolysis of urea ($CO(NH_2)_2$) into ammonium (NH_4^+) and carbonate (CO_3^{2-}). In a calcium-rich environment (provided by a calcium chloride solution), carbonate ions precipitate as calcite ($CaCO_3$) crystals [35-37].

The improvement is dual-phased: (i) Chemically, the reaction consumes sodium ions and raises the local pH near the microbial cell or enzyme, promoting flocculation. (ii) Physically, the precipitated calcite acts as bio-cement, coating particle contacts, bridging gaps between grains, and clogging pore throats. This results in a marked increase in unconfined compressive strength and, most importantly for dispersive soils, a drastic reduction in erodibility. Studies by Moravej, Yuan, and others confirm that MICP-treated dispersive soils can withstand standard pinhole tests. Furthermore, research by Wu Zeju indicates that the bio-cemented fabric exhibits remarkable resilience, maintaining improved properties even after repeated wet-dry and freeze-thaw cycles, addressing a key concern for long-term durability [38].

3.5 Other Novel Materials

The search for effective and sustainable additives continues. Cellulose nanofibers (CNFs), derived from plant biomass, can form a dense, reinforcing nanofiber network within the soil matrix, improving tensile strength and crack resistance [39]. Recycled glass powder, when finely ground, can exhibit pozzolanic activity, while its angular particles also contribute to better particle interlocking and density.

4. Conclusions and Prospects

Research on dispersive soils has matured from initial hazard recognition and mechanistic understanding to the development and refinement of a diverse portfolio of improvement technologies. While traditional chemical stabilization (e.g., with lime or gypsum) and the use of established pozzolanic materials like fly ash are well-understood, contemporary challenges demand solutions that are not only technically sound but also environmentally sustainable and cost-effective. The current research trajectory is decisively oriented towards “green” and resource-conscious strategies:

1) Development of Green and Sustainable Materials: The utilization of industrial by-products (slags, fly ash, coal gangue), agricultural/industrial wastes (lignosulfonates, biopolymers like xanthan gum), and recycled materials (concrete powder, glass) embodies the principles of a circular economy, transforming waste streams into valuable engineering resources.

2) Innovation in Biotechnology: MICP and EICP stand out as frontier technologies with high ecological compatibility. Their ability to create natural cementation in situ, with minimal ground disturbance and low energy input, presents a highly attractive alternative. Future work is optimizing bacterial/enzyme consortia, delivery methods, and treatment uniformity for large-scale field applications.

3) Composite and Hybrid Improvement Strategies: Recognizing that no single method is perfect, research is increasingly focusing on synergistic combinations. Examples include lignosulfonate-fiber composites, bio-cementation combined with a small dose of pozzolanic ash, or the sequential application of a chemical flocculant followed by a biopolymer stabilizer. These hybrid approaches aim to harness the complementary strengths of different mechanisms — for instance, rapid initial stabilization from chemicals followed by long-term bio-cementation.

To advance the field, future research should delve into several key areas:

Material Innovation: Sourcing and engineering even more cost-effective, high-performance, and locally available amendments, particularly from waste streams.

Micro-Mechanistic Insights: Employing advanced micro-analytical tools (SEM, XRD, MIP, AFM) to quantitatively elucidate the nano-scale and micro-scale interactions between soil particles and different amendments.

Long-Term Performance and Durability: Conducting systematic, long-term field studies and accelerated laboratory tests to evaluate the persistence of improvement under realistic environmental stressors (cyclic wetting-drying, freezing-thawing, chemical leaching).

Standardization and Guidelines: Developing more robust, standardized identification protocols and establishing risk-based, graded design guidelines for the selection and application of improvement techniques tailored to specific project types (e.g., earth dam core vs. highway subgrade) and climatic zones.

By addressing these challenges, the geotechnical community can move towards more reliable, economical, and environmentally responsible management of dispersive soils, thereby safeguarding critical infrastructure against this hidden geotechnical threat.

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