Asia Pacific Science Press

Journal of Advances in Engineering and Technology
ISSN(O):3005-7507
ISSN(P):3005-7493
Vol. 3 No.2 (2026)

Stability of Geogrid-Reinforced High-Fill Slopes: A Review of Experimental and Numerical Advances

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Abstract: Geogrid Reinforcement Technology is one of the most widely used slope stabilization techniques in modern geotechnical engineering. In the following paper, the recent research achievements and development trends of geogrid reinforcement technology will be systematically introduced from the perspective of four aspects: interface interaction characteristics, strength properties of the reinforcement, numerical simulation and analysis, and long-term service performance. Based on the existing 40 core publications in the related field, the following conclusions can be drawn: Firstly, the study of interface characteristics has evolved from the analysis of the macro level to the exploration of anisotropy characteristics, cyclic responses, and environmental degradation effects; however, there is still a big gap between the micro-mechanisms and the macro-analysis; Secondly, the results of the triaxial test show that the main function of the geogrid is to improve the cohesion of the soil; Thirdly, the problem of particle fragmentation in special soils, such as calcareous sand and coral sand, has become a key point in the current study. (3) Numerical simulation methods have developed from traditional macroscopic finite element analysis to FEM-DEM coupled multi-scale methods. The application of green reinforcement materials and new structures has expanded the engineering application range of numerical simulations; (4) the study of long-term performance has changed from empirical judgment to full-scale monitoring and data assimilation, while long-term prediction models under coupled conditions of multiple fields still need improvement. This paper aims to identify the gaps of current research and forecast the direction of future study based on a review of the current status of related research, which can serve as a comprehensive reference for related studies.

Keywords: Geogrid; Reinforced Soil; Slope Stability; Interface Characteristics; Triaxial Test; Numerical Simulation

Published: Mar 31, 2026

DOI: https://doi.org/10.62177/jaet.v3i2.1214

1. Introduction

1.1 Research Background and Importance

The geogrid reinforcement technology was invented in the late 1970s in accordance with the theory of reinforced soil developed by French engineer Henri Vidal. It has been over four decades since the geogrid reinforcement technology was invented and applied in the field. The geogrid reinforcement technology is now a very important technology in the field of geotechnical engineering. The geogrid reinforcement technology is very simple in principle. The geogrid reinforcement technology is developed in accordance with the idea of placing geogrids in layers in the soil mass. By virtue of the frictional force between the geogrid and the soil mass and the passive resistance of the transverse ribs, it is possible to improve the overall tensile properties of the soil mass so that the soil mass and geogrids are combined in terms of their force-bearing properties. The geogrid reinforcement technology has been widely used in various projects because it is convenient in use, has low costs, and is environmentally friendly. With the continuous advancement of relevant research and the accumulation of extensive engineering experience, the understanding of the reinforcement mechanism of geogrids has evolved from the description of the macroscopic characteristics to the establishment of a systematic theory involving the coupling of multiple scales and multiple fields. The current research on the reinforcement mechanism of geogrids can be generally divided into three aspects. The first is the interface characteristics between the soil and the geogrids. This began with the dual mechanism interface model proposed by Jewell and Milligan in 1989 [1], which has since been extended to incorporate anisotropy [6], responses to cyclic loading [8,10], and environmental degradation [11,12]. The second strand is the mechanical properties and testing methods in reinforced soil. This has mainly been achieved through direct shear tests [3-5] and triaxial tests [15-17,21] that have analyzed and determined the constitutive behavior of the mechanical properties of reinforced soil. The third strand is the analytical methods used in the stability analysis of reinforced slopes. This has progressed from the limit equilibrium methods that were first employed to the popular and recent finite element methods [29-30,32], and then to the recent multi-field coupling and multi-source assimilations [35-36], with the overall analytical methods being refined and coupled with each other.

1.2 Research Objectives

A review of the core literature in this field has identified three critical scientific questions and research gaps. Firstly, there is a lack of integration between the microscopic and macroscopic responses in interface property research. Although the anisotropy of interface strength and the effects of factors such as normal stress and grid type on interface strength have been identified in research, and even generalized equations for interface strength have been proposed [6], the results have not been effectively integrated into the overall analysis of slope stability. Numerical simulation results relevant to this field also show that the interface constitutive models commonly used in the finite element method are too simple and are not effective in reflecting the spatial and directional variations in interface strength.

Secondly, the research on the reinforcement of special soils is still in the phenomenological description stage and lacks sufficient modeling. With the development of engineering projects into complex geological zones, the reinforcement of special soils such as calcareous sand and coral sand has received increasing attention. Through the research carried out so far, it has been found that particle fragmentation plays a very negative role in the reinforcement of special soils [16-18]. Some scholars have studied the influence of the grid's aperture and tensile strength from the perspectives of macro and micro. However, there is still no consensus on the method for quantifying the influence of particle fragmentation and incorporating it into the actual design. Although the research carried out using 3D printing technology has investigated the corresponding relationship between the aperture and the particle size, providing a new direction for the refined design [26].

Lastly, the study on the coupling of multiple fields and long-term performance has a deficiency in that there is "abundant short-term testing but weak long-term predictive capability." Various studies have focused on the degradative influence of factors like wet-dry cycles, freeze-thaw cycles [11], moisture content, and compaction degree [12] on the interface properties. In addition, some studies have drawn long-term performance laws based on full-scale monitoring results, while other studies have carried out long-term behavior studies through numerical simulations based on creep and environmental factors. However, there is still a lack of theoretical models for extrapolating short-term environmental impacts.

These research gaps have resulted in three engineering practice challenges related to the design of geogrid-reinforced slopes. Firstly, the difficulty in utilizing the results of interface research lies in the fact that the results are difficult to transform into engineering parameters. Secondly, the design of special soils is based on experience rather than theory. Thirdly, the lack of long-term performance prediction capability makes it impossible to assess the safety reserves of the slopes during the service period. Therefore, it is of great importance to organize the existing research results systematically, clarify the development strategies, and identify the key scientific issues in order to promote the theory of reinforced soils and push the innovation of engineering applications.

Based on the above background, this paper reviews and synthesizes 40 typical studies on the stability of geogrid soil slopes through the following structure: In Section II, the research on the characteristics of the soil-geogrid interface is discussed, including the mechanisms, influencing factors, and patterns of special states; In Section III, the test results on the mechanical properties of reinforced soil are presented, including direct shear tests, triaxial tests, and long-term tests; In Section IV, the development and recent achievements in the stability analysis methods of reinforced soil slopes are analyzed; In Section V, the research trends and suggestions on the future research direction are presented.

2. Study on Soil-Geogrid Interface Characteristics

2.1 Theoretical Basis and Testing Methods

The interface interaction of the soil with the geogrids represents the heart of the entire reinforcement technology, as well as the most critical scientific problem associated with this technology. Already as early as the 1980s, fundamental work was carried out by Jewell & Milligan [1]. In this context, the study suggested a new approach to understanding the properties of the geogrids as continuous structures consisting of an infinite number of units capable of carrying loads, with the reinforcement effect of the geogrids being based on the properties of two types of resistance: friction resistance at the interface of the grid with the soil, as well as passive resistance of the grid's transverse ribs against the soil, a so-called "dual mechanism model" of understanding the principles of the interaction of the soil with the geogrids, which remains a fundamental theory until now.

Regarding the materials used, a systematic review was performed by Al-Barqawi and Shanableh in 2021 [2]. In their study, they focused on the analysis of the correlation between the properties of the materials used, design concepts, and structural configurations of the geogrids made from different types of polymers, including PET, PP, HDPE, etc. It was clearly stated that the type of used polymer, the method of production, and the form of the structure directly affect the mechanical properties and lifespan of the geogrids. For example, biaxial geogrids can be used in bidirectional loading conditions, while uniaxial geogrids are mainly used in reinforced earth retaining walls. Moreover, triaxial geogrids have the ability to provide isotropic bearing capacity. These findings provide significant references for the selection and design of materials in engineering applications. To explore the problems related to the interface, standardized test methods must be employed. Stacho et al. carried out tests using the large-scale direct shear test method to obtain the characteristics of the soil-grid interface's shear strength, as well as the correlation between the test conditions and the test results [3]. In the case of "asymmetric interfaces," i.e., when the soil properties on the two sides of the grid are different, Liu et al. carried out direct shear tests using the large-scale direct shear test method [4]. The test results show that the moisture content plays a significant role in the interface's strength when dealing with silty clay soils; the maximum value is achieved when the moisture content is optimal, and the interface's strength is increased with the compaction.

For the gravel-soil mixtures, Wang et al. found the following more specific quantitative patterns through the experiments they carried out: when the normal stress is not higher than 30 kPa, the peak interfacial stress increases linearly with the compaction degree; when the shear rate is 1.5 mm/min, the interfacial stress can reach its maximum value [5]. In addition, they found the following interesting phenomenon: with the increase in compaction, the "pseudo-cohesion" at the interface increases, and the "pseudo-friction angle" decreases.

2.2 Interface Anisotropy and Generalized Strength Equation

Past interface strength tests were carried out along a single direction, while engineering loads are normally not aligned along a single direction. To deal with this, a unique testing device was created, as presented by Zhang et al, which allows the direction of shear to be changed during a test. Shear tests were carried out on bidirectional and tridirectional geogrids at different angles: 0°, 45°, and 90° [6].

The results show a significant finding in the following way: under the same normal stress conditions, the interface's shear strength depends on the direction of the shear and thus directly confirms the high level of anisotropy in the interface between the soil and the grid. Further analysis has shown that the anisotropy in the interface between bidirectional grids and the soil is more significant than the anisotropy in the interface between the soil and the triaxial grids. Moreover, the size of the soil's particles plays an important role in this anisotropy.

Udomchai et al. changed the focus of their research to recycled materials and carried out large-scale direct shear tests on the interface characteristics between recycled asphalt pavement (RAP) and jute geogrids [7]. They identified the parameter D/FD (where FD is the content of recycled particles less than the opening of the geogrid) as the main parameter governing the interface strength and established the generalized interface strength equation as $\alpha = a(D/FD) + b$. The constants in the equation were found to be dependent only on the type of recycled material and not the type of geogrid material. The equation can be used as a valuable tool in the design calculation for the use of recycled materials in pavement engineering.

2.3 Effects of Cyclic Loads and Environmental Factors

During the service life of the structure, the structure will inevitably be subjected to cyclic loading such as traffic loading and seismic loading. The changes in the properties of the interface subject to cyclic loading have a direct influence on the long-term stability of the structure. In the study by Jiang et al. the influence of the gradation of the soil on the dynamic shearing properties at the interface between the coarse-grained soil and the geogrid was investigated through cyclic direct shearing tests [8]. It was concluded that if the content of the coarse-grained soil is high, the shearing stiffness K increases with the increase in the maximum particle diameter d_max, while the damping ratio D decreases. Optimal results were obtained at a ratio of 0.073.

In addition, Zhang et al. studied four-directional geogrids with regard to their cyclic shear behavior at the interface with sandy soils [9]. It is evident from the findings of this study that the peak interface strength is directly proportional to the increasing normal stress and the displacement amplitude of the shear. Furthermore, it is evident that increasing the normal stress and the displacement amplitude reduces the number of cycles to peak interface strength. In addition, Ferreira et al. studied the interface between HDPE geogrids and residual soils, revealing different evolutionary patterns of the interface under cyclic loading [10].

Besides mechanical loading, environmental factors are also important considerations in the engineering design of cold regions and areas with alternating wet and dry conditions. The effects of wet-dry cycles and freeze-thaw cycles were systematically studied by Zhou et al. [11]. The results indicated that these two types of cyclic loading can cause the mechanical properties of the geogrid material to deteriorate, which in turn affects the synergy between the soil and the geogrid material. In addition, the deterioration becomes more severe with the number of cycles.

In the case of loess, which is widely distributed in China, Zhang conducted research on this material [12]. In this regard, it was revealed from the experiments conducted by Zhang that when the moisture content does not exceed the plastic limit, a higher moisture content results in a shift in the curve from a softening type to a hardening type in the shear stress-shear displacement curve. At the same time, a significant reduction in cohesion and friction angle at the interface occurs. In regard to compaction degree, when this degree reaches 90%, a significant increase in thickness in the zone of shearing occurs. Therefore, in reinforced loess engineering, this degree preferably should not be lower than 90%.

2.4 Particle Morphology and Micromechanism

In recent years, the influence of the morphological properties of soil particles on interfacial shear properties has become a popular topic in the field of academia. In the study carried out by Li et al., a comprehensive method of direct shear tests and discrete element method simulations was used to investigate the influence of particle size and roundness of the gravel particles on the interface of the gravel grid [13].

Their results were conclusive; the reinforced soil interface displayed its characteristic shear softening behavior. Peak and residual shear stresses decreased by 15% to 16% as the particle roundness increased from 0.35 to 0.75. On the other hand, as the particle size increased from 5 mm to 13 mm, the internal friction angle increased by 10.8%, and the apparent cohesion increased significantly by 144%. At the micron-scale, they observed a unique "peanut-shaped" distribution of shear contact forces, and the tangential contact forces displayed a "petal-shaped" distribution.

In a study by Wang et al., the researchers emphasized the content of fine grain materials by evaluating its impact on the shearing behavior of geogrid-reinforced gravelly soil [14]. The findings showed that with increasing content of fine grain materials in the soil, its peak strength and shearing parameters initially increased and then decreased. At the same time, a significant relationship was established in which a lower content of fine grain materials coupled with a normal stress led to higher shearing dilatancy at the interface.

3. Reinforced Soil Mechanics and Experimental Studies

3.1 Triaxial Tests and Strength Characteristics

Triaxial compression tests still represent the most fundamental and widely used approach for the study of the mechanical properties of reinforced soils. In the study by Zakarka et al., the influence of density and the non-uniformity coefficient was investigated on the mechanical properties of single-layer geogrid-reinforced sand and gravel soils through consolidated drained triaxial tests [15]. From the results obtained in the study, it is evident that the pressure has a critical influence on the effectiveness of the reinforcement process, with higher pressure resulting in the reduction of the effectiveness of the grid. Moreover, the deviatoric stress values for the gravel soils are higher compared to the sandy soils. The strength parameters of the soils have shown that the grid has the greatest influence on cohesion but results in a reduction in the friction angle in most test conditions.

For the special fill material of calcareous gravelly sand, the results of triaxial tests conducted by Liu et al. are as follows: the effectiveness of reinforcement in strengthening the soil is obvious, and the fragmentation of particles has a significant negative influence on the strengthening effect of reinforcement [16]. In the study of layered reinforcement, Cui et al. tested composite materials with the following components: geogrid, sand, and clay [17]. It is shown in the study that the layered arrangement of reinforcement has a significant influence on the performance of composite materials. The advantages of different materials can be fully utilized through the design of layered composite materials in a reasonable way.

With the improvement of experimental methods, 3D printing technology has also been used in the construction of geogrids. Shi et al. used 3D printing technology to prepare triaxial geogrids, which were used to study the mechanical properties of reinforced marine coral sand-clay mixture materials [18]. It was found that smaller amounts of clay, more reinforcement layers, and higher confining pressures significantly improved the mixture's strength and cohesion. In addition, a linear relationship was found between the rate of particle breakage and fractal dimension.

From the numerical simulation point of view, Liu used the three-dimensional discrete element method to investigate the macro-micro response of the reinforced coral sand subjected to high confining pressure [19]. It was observed that the mechanical responses of the reinforced and unreinforced specimens showed significant differences at high confining pressure, with the reinforced specimens displaying obvious hardening characteristics and suppressing the phenomenon of strain softening and swelling deformation. In addition, Zakarkaa and Skuodis put forward a parameter calibration method for the grid-reinforced soil model based on the triaxial test results and identified the sensitive parameters that provided parameter support for the subsequent numerical simulation [20].

3.2 Large-Scale Triaxial Tests and Coarse-Grained Soils

For engineering practice, such as highway and railway embankments, reinforcement of coarse-grained soils is a common practice. In this area, small-scale triaxial tests are no longer suitable, and the only method used in this area of research is the large-scale triaxial test.

Liu et al. took three typical gravel soils from Xinjiang and carried out large-scale triaxial tests to study their reinforcing effect [21]. The results showed that the internal friction of the soil did not change significantly before and after reinforcement, which means it remained constant. The increase in strength mainly resulted from the increase in cohesion between the soil particles. Regarding volumetric strain, it decreased significantly with the increase in confining pressure for reinforced gravelly soil. Moreover, with the increase in confining pressure, the difference in volumetric strain between reinforced and unreinforced soil became greater.

An in-depth study on the behavior of the shear response of calcareous gravelly sand was carried out by Chen et al. [22]. The study compared the results obtained through large-scale triaxial tests and discrete element simulations, which indicated that the soil has stronger resistance to strain softening compared to calcareous coarse sand; however, it is also found that the soil is prone to fragmentation. Regarding the reinforcement mechanism, it is found that the main mechanism of reinforcement using geogrid is that it restricts the lateral movement of the soil, which is equivalent to the suppression of volumetric shear swelling behavior of the soil, which in turn increases the peak value of the shear stress.

3.3 Reinforcement of Clayey Soils and Special Soils

In recent years, studies on reinforcement using clayey soils as fill materials have gradually become a focus of academic attention. In the study conducted by Wang et al., the authors carried out a systematic investigation of the mechanical properties of clay soils reinforced with geogrids using triaxial tests and discrete element simulations [23]. The results showed that the peak strength and cohesion of the reinforced soil can be significantly enhanced with an increasing number of reinforcement layers, whereas the effect on the internal friction angle is limited. Meanwhile, it is verified that the stress-strain relationship of reinforced soil follows the classical Duncan-Zhang model. Through discrete element micromechanical analysis, it is found that the reinforcement can reduce the fluctuation of soil porosity, significantly improve the interparticle contacts, and densify the soil structure.

With regard to the reinforcement layers' influence, minor differences were noted depending on the soil type used. In their study on microgrid-reinforced sandy soil, Teles Júnior et al. noted that an increase in reinforcement layers significantly increases the soil's strength parameters, even causing a change in the soil's stress-strain curve from strain softening to strain hardening [24]. On the other hand, in their study on granitic residual soil, Deng et al. noted a "marginal effect" in the reinforcement influence, whereby the reinforcement effect of the two layers was not in a simple linear relationship, and the reinforcement effect of the second layer showed a diminishing trend [25]. Nevertheless, the studies by both authors validate an important fact: the fundamental principle governing geogrid reinforcement in soil is an increase in cohesion, thereby justifying the quasi-cohesion increment formula.

3.4 Advanced Manufacturing Technologies and Novel Materials

Significant developments have been observed in the manufacturing domain, providing new means of conducting advanced studies on geogrids through innovative means such as 3D printing. Oliveira and Falorca avoided the usage of existing pre-fabricated grids by designing test specimens with different apertures and stiffness values through CAD and 3D printing [26]. In the study, the mechanical properties of two-layered soil consisting of a base layer of granite aggregate and a subgrade layer of sandy soil were examined.

The results of their research produced a very pragmatic conclusion: the reinforcement effect is often optimal when the ratio of the grid aperture and the median soil particle size is close to 1. Moreover, they found nonlinear characteristics of interfacial load transfer, indicating that the optimal interfacial behavior is not necessarily dependent on the grid's stiffness.

With regard to numerical model application, Zakarka et al. calibrated the hardened soil model parameters based on experimental results obtained during a triaxial test [27]. The study showed that specific values of the power index 'm' and the unloading-reloading modulus 'Eur' are required to improve the model's accuracy in matching experimental results, which has important engineering implications.

3.5 Macro-Micro Correlation and Particle Fragmentation

To clarify the reinforcement mechanism, it is crucial to establish the link between the macro-mechanical response and micro-particle behavior. Luo et al. specifically focused on this, using the discrete element method to extensively study the macro-micro mechanical behavior of geogrid-reinforced calcareous sand under three-dimensional loading [28].

The findings indicate that reducing the aperture size of the geogrid and increasing its tensile strength both enhance the macro-mechanical properties of the reinforced body. At the microniveau, particle failure is primarily governed by shear strain and confining pressure, while the confining effect of the grid partially suppresses soil swelling deformation. By examining the interaction between granular particles and the grid, this study provides a clear explanation for the intrinsic source of strength enhancement in reinforced soil, offering valuable microniveau insights for a deeper understanding of the reinforcement mechanism.

4. Numerical Simulation and Engineering Applications

4.1 Macro-Scale Finite Element Analysis

Finite element analysis has become a crucial numerical tool in the design of reinforced soil structures. Sundaravel and Dodagoudar employed the finite element method to analyze the performance of reinforced soil retaining walls, comparing and evaluating the applicability of different constitutive models such as Mohr-Coulomb and hardening soil models [29]. This provides a reference basis for subsequent numerical simulations of reinforced soil structures.

Samal et al. performed static stability analysis on bamboo grid-reinforced slopes using MIDAS GTS NX finite element software, exploring the feasibility of applying such green reinforcement materials in slope stabilization projects [30]. Onur et al. also employed the finite element method to investigate the enhancement of overall slope stability through geogrid reinforcement, conducting a quantitative analysis of the relationship between reinforcement parameters and safety factors [31].

Systematic research on the reinforcement mechanism and design methods for the tension type of reinforced earth retaining walls has been carried out by Sun et al. [32]. The structural responses of the geotextile strips and the geogrids as the reinforcement materials were compared in the research carried out by Sun et al. The results show that the tension type of reinforced retaining walls can reduce the vertical stresses in the walls and the earth pressures on the wall panels.

In the control of the horizontal deformation of the walls, the wrapped geogrids are found to be more effective compared to the geotextiles. However, in terms of safety, deformation, cost, and difficulty in the construction, the economic efficiency and simplicity in the construction process of the walls using the geotextiles are more effective. Xu et al. carried out the analysis on the displacement characteristics of reinforced earth retaining walls with super-high fill slopes subjected to the loads from the structures on the crest using the FLAC3D software [33]. The analysis resulted in the findings on the significant differential settlement in the wall and the slope behind the wall. This would be highly useful in the layout and designing of the structures on the crest. Yoo et al. carried out the research on the reinforcement efficiency of the geogrid-reinforced slopes using the finite element analysis method [34]. They validated the reliability of the model using the field measurement data.

4.2 Multi-Scale and Multi-Field Coupled Analysis

Computational advancements have allowed for multi-scale simulations, which can perform cross-scale studies from microscopic interfaces to macroscopic structures. Zhao et al. carried out multi-scale numerical simulations using a coupled finite element and discrete element approach for the analysis of reinforced soils using geogrids, and the intrinsic mechanisms of reinforcement were studied at the mesoscopic scale [35]. It can thus be shown that multi-scale models can simulate the macro-micro coupling in reinforced soils quite well. Reinforcement of soils can modify the internal force chains and anisotropy of particle contacts in soils, and these are the microscopic mechanisms for the macroscopic strength of reinforced soils.

Multiphysics coupling analysis is also a research hotspot in this area. Ng et al. carried out a research on the response characteristics of unsaturated soil-reinforced slopes under hydraulic-mechanical coupling conditions through numerical analysis and centrifuge tests [36]. It is found that the hydraulic coupling has a great effect on the stability of the unsaturated reinforced slope under rainfall conditions; the reinforcement measures can well control the problems of deformation under the condition of suction loss; and the results of the centrifuge tests verify the rationality and reliability of the numerical model.

4.3 Long-Term Performance and Field Monitoring

Long-term performance studies are of great importance in the development of a solid base for the achievement of full-life-cycle design of reinforced soil structures. Bathurst and Allen discussed the long-term performance characteristics of geosynthetic-reinforced retaining walls and slopes based on field monitoring results of full-scale structures, with a focus on the importance of rational design and construction quality for long-term structural stability of reinforced soil structures [37].

Abdi and Zandieh studied the long-term mechanical performance of reinforced soil structures subjected to combined material creep and environmental effects through numerical simulations and proposed relevant long-term performance prediction methods [38].

Gaur et al. carried out a comparison of the characteristics of the pull-out resistance of various geogrids through the integration of the results of the field pull-out tests and numerical simulation [39]. It has been found that the M65 geotextile strips show 20% higher initial pull-out strength in sandy soils compared to the biaxial geogrids. However, the ultimate pull-out strength is found to be 8% less in the M65 geotextile strips. It has been found that the geotextile strips are more appropriate for use in the construction of low-grade roads and other backfill works, while the geogrids show more advantages in the construction of high-grade roads.

Gör et al. studied the improvement in the stability of the slope through the use of geogrid reinforcement by model tests and numerical analysis [40].

4.4 Engineering Application Cases

The applicable theoretical and experimental results have been used in various engineering practices. To illustrate, Reference [32] carried out optimization of essential design parameters of tension-reinforced retaining walls in soil, based on the UAE's heavy haul double track high-speed railway project. Reference [33] performed displacement analysis of super-high embankment slopes with building loads at the crest, which was used as a basis for choosing a building site. Reference [39] carried out in-situ pull-out tests of the NH148B National Highway project in India, verifying the applicability of reinforced solutions with geotextile.

Collectively, the engineering examples show that the theoretical results of laboratory testing, numerical simulation, and theoretical analysis are gradually transforming from theoretical study into engineering practice, offering strong backing for the advancement of reinforced soil technology.

5. Conclusions

This paper focuses on the stability of geogrid-reinforced earth slopes. By systematically summarizing and synthesizing 40 core papers, the recent research achievements, existing difficulties, and development directions in the future can be comprehensively outlined as follows:

(1) Research on the characteristics of the interface between soils and geogrids has formed a comprehensive research framework. This framework includes the theoretical basis, the development of test methods, the exploration of characteristic laws, and the in-depth study of the micro-mechanisms. In addition, the academic community has gained a relatively clear understanding of the influence of factors such as interface anisotropy, cyclic response, environmental degradation effects, and particle morphology on the interface. However, the key difficulty lies in the fact that these advanced micro-mechanisms have not been effectively integrated into the analysis framework at the macro-level.

(2) The research on the strength characteristics of reinforcing elements has shown a clear path of extension in the following aspects: expanding from ordinary soils to special soils while incorporating advanced technologies to build connections between the macro and micro scales. A large number of triaxial test results have confirmed the basic mechanism of the reinforcement effect on the strength characteristics of soils—increasing cohesion. At the same time, the particle fragmentation characteristics in special soils such as calcareous sand and coral sand are hot research fields. It is noteworthy that the application of 3D printing technology has provided a new means for improving the research on the parameters such as grid size and stiffness.

(3) Numerical simulation techniques are progressing rapidly. Analytical techniques have developed from traditional macro-scale finite element analysis to FEM-DEM multiscale coupling and hydromechanical multiphysics coupling analysis. At the engineering application level, the emergence of green materials such as bamboo grids and new engineering structures such as tension-supported retaining walls has greatly increased the engineering applicability of reinforcement technology. The use of field monitoring combined with data assimilation techniques has greatly improved the reliability of numerical simulation models.

(4) In the aspect of the study on the long-term performance, the industry has gradually shifted its focus from the traditional empirical estimations to the full-scale monitoring and data assimilation methods. Nevertheless, the prediction models that can take into account the effects of multi-field coupling in the long-term performance analysis have not yet been developed. Besides, the studies on the pull-out resistance and the long-term durability of new types of reinforcement materials, such as geotextile tapes, are still in the primary stage and need to be further explored.

(5) Considering the present research status and existing gaps, the following four aspects are the direction for the future research: Firstly, the establishment of theoretical models with accurate micro-macro correlations; secondly, the promotion and establishment of the design theory for the reinforcement of certain soils; thirdly, the establishment of a science-based method for predicting the service performance; and fourthly, the promotion and development of the research and engineering applications of green reinforcement materials so as to provide theoretical guidance for the development of geogrid reinforcement technology.

Funding

This work was supported by the Xi'an Si yuan University President's Fund Research Project (Project No. XASYB24ZHD05). Investor: Xi'an Siyuan University, Investment Amount: 60,000 RMB.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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