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Review

A Review of the Stability Analysis of Roadbed Slope and Prevention Technologies

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Abstract

Roads are important infrastructure for a country's economic and social development. The stability of subgrade slopes, as one of the most prominent engineering issues in roads, is of great significance for the assessment and analysis of the stability and prevention of subgrade slopes. In order to further promote the development of roadbed slope stability and prevention engineering, improve the design level of road engineering slope engineering disaster management projects, and reduce the cost of engineering investment, this paper starts from the category of roadbed slope damage form, respectively, for the research method of slope stability, slope stability influencing factors, and slope damage prevention and control measures to carry out a review, based on the current status of the research and the future direction of research. It was found that the damage forms of roadbed slopes are roughly divided into four categories: landslide, avalanche, slump, and spalling. A field test is the most accurate and practical means of evaluating slope stability research. The current analysis of the factors affecting slope stability is too independent, and there is a need to analyze the coupling relationship between the various influencing factors as a whole. Furthermore, the paper outlines a range of preventive measures and control strategies, including slope reinforcement techniques, vegetation cover, and drainage management, which have proven effective in reducing slope failure risks. These results provide critical insights into the design of more resilient roadbed slopes, with potential implications for reducing engineering costs and improving the safety and sustainability of road infrastructure.

Keywords: road engineering; slope stability; control; overview

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1. Introduction

With the rapid development of China's highway industry, as of the end of 2022, the total mileage of China's highways is 5,354,800 km, and highway construction will inevitably involve a large number of slope engineering problems. With the expansion and development of the scale of the new round of economic construction, slope engineering disaster problems in the form of landslides will become more and more frequent [1]. A large number of slope engineering disaster problems often lead to an increase in the cost of construction and delays in the construction period, and some even occur during the operation of the project; there are potential hazards, resulting in serious impacts on construction projects and even threatening the safety of human life. Therefore, it becomes especially important to study slope stability. In recent years, many scholars have conducted a series of studies on the stability of roadbed slopes, and KARDANI N et al. [2] indicated that rainwater infiltration, snow melting, glacial melting, groundwater rise, physical and chemical weathering of geotechnical bodies, and ground vibration caused by earthquakes or human activities may cause damage to slopes either individually or jointly. SUMAN S et al. [3] showed that whether a slope is stable or not is basically controlled by the ratio of effective shear strength to the acting shear stress; in addition, several key parameters such as slope geometry (height and slope angle), shear strength parameters (angle of internal friction and cohesion), pore water pressure, and soil properties (unit weight and degree of saturation) play a crucial role in slope stability. Lv Qing [4] concluded that the slope stability analysis methods can be divided into four categories: bar division method, limit analysis method, slip line method, and numerical analysis method. Among them, the most widely used slope stability analysis method in engineering practice is the strip partition method. The strip partition method is characterized by treating the landslide body as a rigid body, adopting the Mohr–Coulomb damage criterion on the hypothetical slip surface, considering only the static equilibrium conditions, and solving the problem by analyzing the equilibrium of forces of the landslide body in the limit equilibrium state. Gordan et al. [5] evaluated the stability of slopes under the effect of earthquakes using artificial neural networks and particle swarm optimization. Qi et al. [6] conducted a comparative study of integrated meta-heuristics and machine learning methods, including logistic regression, decision trees, random forests, support vector machines, multilayer perceptron artificial neural networks, and gradient propulsion machines. Bishop [7] first proposed the definition of the safety coefficient and then, by assuming that the force between the soil strips is in the horizontal direction, determined the normal force between the soil strips, which makes an important improvement to the traditional Fellenius method and models a simplified method. Among them, both the Swedish arc method and Bishop's method determine the safety factor by means of moment balance. Fell and A. Uromeihy et al. [8,9] applied the improved method of risk evaluation to landslide geohazards and discussed issues such as guidelines for acceptable risk and used the zoning map of landslide geohazards to evaluate the potential risk of landslide hazards, and based on the fuzzy set theory, the potential risk indicator of each shadow was calculated for each factor, factors used to calculate the potential risk index. In summary, for research on roadbed slope stability, rich research results have been achieved at home and abroad. Researchers at home and abroad start from the type of slope damage and use a variety of research methods to explore the stability of slopes; however, due to the limitations of experimental conditions, there are advantages and disadvantages to all types of research methods. In the stability study of slopes, the most important thing is to determine the advantages and disadvantages of the research method and the scope of application, so that it can be more accurately applied to slope stability research methods. The factors affecting slope stability are divided into internal and external factors, and a comprehensive analysis of the factors affecting slope stability is of great significance to the field of road engineering, and it is also conducive to the proposal of more efficient measures to prevent and control slope damage.

This paper integrates the existing forms of slope damage, summarizes the types and advantages and disadvantages of current research methods from both experimental and theoretical aspects, deeply analyzes the role of internal and external factors of slope stability, and explores the effective measures of slope protection. The overall goal of this paper is to sort out the existing research results in the field of roadbed slopes and provide theoretical support for possible future research. The research content of this review is shown in Figure 1.

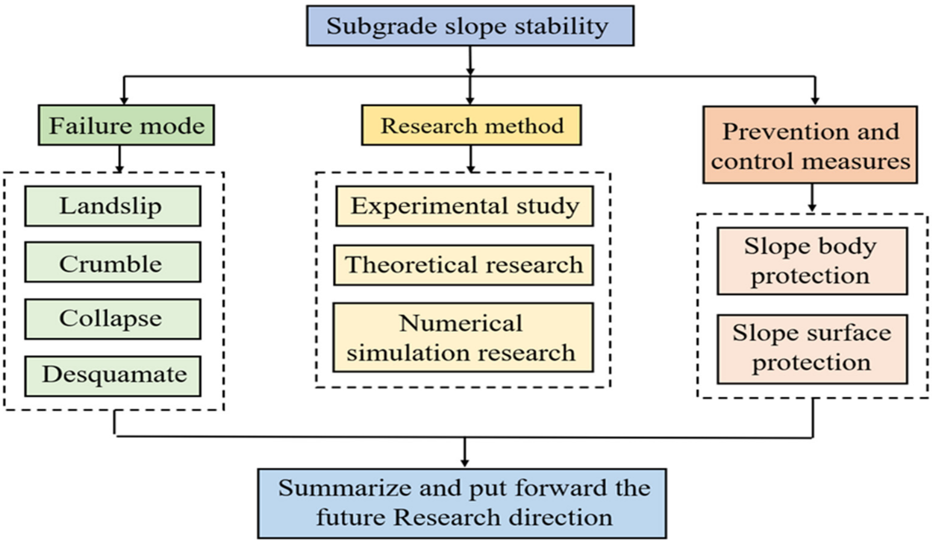

Figure 1. Technology roadmap.

2. Forms of Slope Failure

Roadbed slope damage forms are mainly controlled by the engineering geological conditions of the rock body, especially the structural surface of the rock body, which will produce various forms of damage under the coupled influence of a variety of internal and external factors; in order to ensure the safety and stability of the road, it is necessary to sort out and summarize the damage forms of roadbed slopes and to promote the proposal of efficient prevention and control measures for roadbed slopes. Roadbed slope damage often occurs on the basis of deformation, when the deformation reaches an irreversible degree, so that the displacement, cracks, and inclination of the geotechnical body increases significantly and reaches the critical threshold, the original function or structural integrity of the slope is destroyed, unable to withstand the original load or external influence, and then slope collapse, landslide, and other phenomena occur. Specific forms of slope damage can be divided into the following four forms.

2.1. Landslides

As the most important type of slope engineering issues, landslide problems are also the most studied slope engineering disasters by scholars. People's concern about and research on slope stability first started with the landslide phenomenon. Slope stability analysis and evaluation are also the core of landslide research. Landslide refers to the phenomenon of continuous sliding or flowing of a local or whole geotechnical body along a certain line or surface due to the destabilization of the geotechnical body by internal or external factors [10].

Landslides are one of the most frequent and hazardous geological disasters, especially in areas with soft soil, humid climate, and frequent earthquakes [10]. Landslide susceptibility evaluation refers to qualitatively or quantitatively evaluating the possibility of landslides according to the landslide database, topography, meteorology and hydrology, and other basic geologic environment and disaster-preventing conditions at a regional scale and obtaining the spatial distribution of potential landslides. Since the 1870s, scholars at home and abroad have conducted a lot of research on landslide susceptibility evaluation. Van Westen et al. [11] evaluated landslide susceptibility using a bivariate statistical analysis method of geographic information statistics (GIS) software (GIS 9) with an area in Italy as the research object. Herrera et al. [12] used GB-SAR to obtain the deformation time series of the Portlet landslide located in central Spain, corrected the parameters of the one-dimensional infinite slope model with a series of monitoring data, and derived a model that integrates the clay–plastic properties of the landslide rock and soil bodies, as well as the intensity of the daily rainfall and the amount of dissipation of the superporous water pressure, and used the corrected model for the deformation prediction of landslides. Meanwhile, better prediction results were achieved. Sun et al. [13] inverted the parameters of the Sanmendong landslide in the Three Gorges reservoir area based on a finite element model and then used the inverted parameters to predict the deformation of the Sanmendong landslide under different boundary conditions; Zhao et al. [14] further considered the creep characteristics of the landslide geotechnical body and predicted the deformation of the Huangniba landslide in the Three Gorges Reservoir Area using the Singh–Mitchell creep model simulation in finite element software. Tang et al. [15] carried out seepage and stability calculations based on the finite element method for the reservoir bank landslide with different slip surface morphologies, permeability coefficients, reservoir water level change rates, and bank slope inundation area and finally obtained the mechanism law of the destabilizing hydraulic action of the reservoir bank landslide. Paronuzzi et al. [16] used the finite element method and limit equilibrium method to invert the landslide of Vaion Reservoir, Italy, and the results showed that the main triggering factor of the landslide was the rapid increase in the water table at the foot of the landslide due to reservoir storage, which led to a reduction in the effective stress in the anti-slip section, and the stability of the landslide was reduced by 12% after the storage of the water compared with the pre-storage period.

2.2. Crumble

A landslide is a geological phenomenon in which part or all of the soil body suddenly collapses, tilts, or slides because the slope is affected by external factors, causing the bottom to be crushed, fractured, or generating localized slippage [17], thus losing its original stability. Avalanche is also one of the common forms of slope damage, but it occurs on a smaller scale, with a small degree of damage, and may form mudslides during the accumulation process.

As early as the 1960s, research scholars at home and abroad conducted relevant studies on the vulnerability of collapse disasters [18–22]. However, in the early stages of research, due to the limitations of technology and other aspects, most of the scholars focused on qualitative evaluation, which mainly included the hierarchical analysis method, the multi-criteria analysis method, and so on. With the rapid development of computer technology, remote sensing technology, and GIS technology, the research work involving collapse disaster analysis has become more convenient and precise. Shi Genhua and Goodman et al. [23,24] proposed a new method to analyze the stability of rocky slopes–block theory. The main purpose of this method is to identify the key blocks, so as to determine the potential collapse area, which provides the basis for collapse monitoring and forecasting. Clough A.K [25] introduced a variable factor of safety based on the traditional limit equilibrium method by defining a special curve to reflect the site-specific boundary conditions; Bishop [7] modified the slope failure bar-splitting method by assuming that the slope sliding surface is a circular arc and satisfying both the moment equilibrium condition as well as the force equilibrium condition in the vertical direction but still failing to meet the external force equilibrium condition in the horizontal direction.

2.3. Collapse

Collapse refers to the geological phenomenon of sudden subsidence or collapse of the ground or structures due to partial or total loss of the original stability of the surface or underground structures under the action of external forces or under the action of self-weight, which has the characteristics of landslides and avalanches at the same time. Highway roadbed slope collapse is a common roadbed problem; highway slope collapse disasters are inevitable. After slope collapse, it is generally necessary to clear the square and reset the protection. After removing the collapsed loose squares, the slope of the normal section is steeper, while the slope of the collapsed section is shallower, which often produces the problem of a gradual change in slope rate between the slope of the collapsed section and the slope of the normal section [26].

The causes of roadbed slope collapse are numerous [27], but when categorized from the perspective of slope form, they can be roughly divided into two categories. The first category is the fill slope, in which there are three main reasons for the collapse: respectively, the poor geological environment of the fill section results in the foundation soil being easily damaged, the existence of an unreasonable engineering design program, and the damage caused by external factors. The other category is the excavation slope, and there are also three collapse forms of such slopes: rockfall-type collapse, sliding-type collapse, and flow-type collapse [28]. Zhang Baolong [29], combined with the actual situation of slope damage at K368 of the Huji Expressway, analyzed and determined that poor slope drainage is the main reason for slope damage and, while using the method of finite element modeling and calculation, established a model that considers two kinds of models of slope ground water seepage or not, and the results obtained through the calculations are highly consistent with the actual situation of slope sliding slumps, so as to determine the management plan of slope issues in this case. Qin Shujuan [30], combined with a mountainous highway slope collapse case in China, developed a method of reinforced geogrid repair and reinforcement and accordingly formed a relevant reinforcement program to guide the construction and post-construction monitoring. The results proved that the reinforced slopes can be effective in reinforcing said slopes.

2.4. Flake

Spalling is a phenomenon in which the surface of a slope is gradually loosened by weathering or other adverse weather conditions and is dislodged by gravity or rainfall. Spalling is random in nature, and the dislodged stones or soil clods may pose a threat to oncoming people or vehicles or accumulate on the road surface, affecting safe driving on the road. Ye Wanjun et al. [31] carried out macroscopic crack analysis and an indoor straight shear test on soil specimens under different water content states to investigate the effect of the water content state of the loess body on slope spalling issues. The results showed that with the increase in the number of dry and wet cycles and cycle amplitude, the surface cracks of the soil specimens continued to expand and extend, and the degree of internal structural damage increased, and the spalling problems occurred along the dominant surface when a dominant surface inside the soil body was penetrated.

Xu Jian et al. [32] studied the mechanism and stability of freeze–thaw spalling problems on loess slopes through on-site research, indoor freeze–thaw tests, and calculation analysis. The study showed that the freeze–thaw spalling problem is divided into superficial freeze–thaw spalling, freeze–thaw laminar spalling, and micro freeze–thaw collapse. And with the increase in the number of freeze–thaw cycles, the cohesive force showed an exponential decay trend, and the angle of internal friction did not change significantly; with the increase in water content, the cohesive force showed a decreasing trend, and the angle of internal friction showed a linear decay characteristic.

Overall, the forms of damage can be classified into four types, landslides, crumble, collapse, and flake, and they are often triggered by the coupling of internal and external factors. Among them, landslides and collapses may be triggered by the same geological structure (such as faults) or rainfall events, forming a chain of damage. The phenomenon of spalling leads to the deterioration of the surface of rock and soil masses, increasing the risk of landslides or collapses. In the future, a dynamic correlation model will be established to quantify the evolution law of the failure form under the coupling effect of multiple factors, as shown in Figure 2.

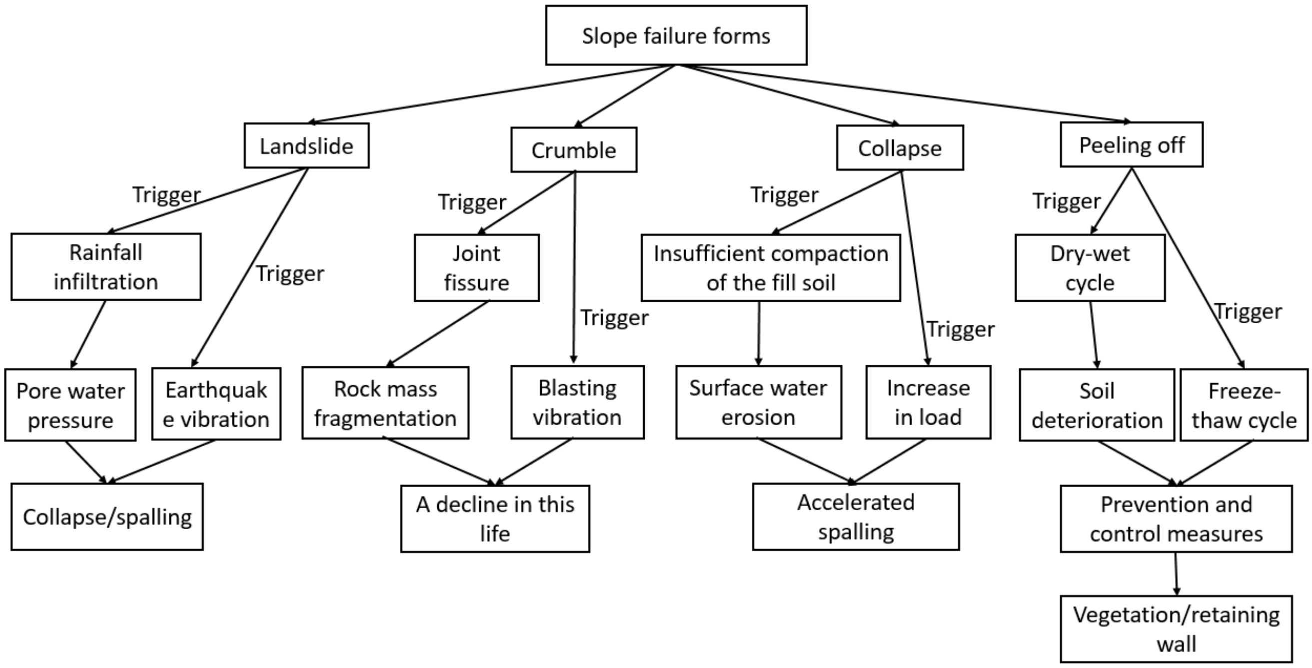

Figure 2. Correlation diagram of slope failure forms.

3. Slope Stability Research Methods

China's geological conditions are rich and complex, influenced by topographic and geomorphic features, and slope stability has become one of the classical problems in geotechnical engineering. Recently, many scholars have carried out a series of studies on roadbed slope stability, including experimental studies [33], theoretical studies [34], and numerical simulation [35] studies. Among them, experimental studies mainly investigate in detail the change rule of geotechnical parameters of slope geotechnical bodies under different conditions through experiments; theoretical analysis mainly establishes the geotechnical body's constitutive equation or mechanical model involving various influencing factors; and numerical simulation research methods, such as finite element, mainly act through the simulation of slope stability under a variety of influencing factors, to further provide data reference for the stability of roadbed slopes in the actual project [36].

3.1. Pilot Study

3.1.1. Indoor Pilot Studies

An indoor test is a universal method to analyze the destructive mechanism of slope stability and investigate the mechanical evolution behavior of slopes, and the indoor test realizes targeted research on slope stability by artificially simulating the influence of the external environment and controlling the variables of technical parameters. Yao Ting [33] analyzed the effect of water content and freeze–thaw action on the shear strength of soil by conducting freeze–thaw tests and direct shear tests on pulverized clay. The study showed that the cohesion and internal friction angle of soil decreased with the increase in water content, and according to the test results, the relationship equation of the change in cohesion and internal friction angle with water content was obtained. Chamberlain [37] analyzed the effect of water content and freeze–thaw action on the shear strength of soil by conducting an indoor infiltration test. Soil samples were analyzed after crystallization-fusion using a freeze–thaw machine, and the authors concluded that both soil porosity and vertical permeability were affected by the freeze–thaw cycle. Song F. et al. [38] used a large triaxial test to study the effect of density of fill, strength, and stiffness of the chamber and the height-to-diameter ratio of the specimen on the stress–strain of geocell-reinforced soil. Zhang et al. [39,40] concluded that the structure and effective porosity of pulverized clay will be changed under the action of freeze–thaw cycles but will no longer be changed when experiencing the action of three to four freeze–thaw cycles; in addition, the shear strength, pore water pressure, and deformation characteristics of the soil will also be affected after experiencing the action of freeze–thaw cycles. Gao Chunjun [41] conducted a series of tests on slope instability caused by drainage pipes in order to find out the crystallization law of drainage pipes. Wang Yan [42] discussed the mechanical state of geocells under different slope rates, loading conditions, and precipitation conditions through the indoor tests of geocell protection of embankment slopes and analyzed the role of geocells in the embankment slope protection system.

The study shows that the greater the slope rate, loading weight, and precipitation, the more obvious the effect of geocell protection on the slope to reduce the displacement and disperse the soil pressure under the geocell. In general, although many scholars have carried out a lot of research on the stability of roadbed slopes through indoor tests and obtained valuable results, there is still a big gap between indoor conditions and materials and the actual site, which leads to a certain degree of deviation between the test results and the actual situation of slopes.

3.1.2. Model Test Studies

In order to further improve the precision and accuracy of studies, researchers have established slope models at different scales [42], all of which are mainly characterized by large-scale machines to simulate the outdoor conditions for testing. Cheng et al. [43] successfully developed rainfall simulation equipment and analyzed the destabilization mechanism of slopes affected by rainfall based on centrifugal model tests. Zeng Wanfu [44] used a model test to simulate the change in slope seepage field in the process of water level descent and found that with the acceleration of the rate of water level descent, the increase in water level difference, and the increase in slope ratio, the slope is more likely to be destabilized and damaged. Cai Jiale [45] determined the mechanism of macroscopic dominant infiltration as well as the trend of fissure extension evolution by using a model box test setup.

Meanwhile, the visualization model test can intuitively observe the change process of the geotechnical body, which is helpful for the mechanism explanation of various types of geotechnical problems [46]. Jingyun Gu et al. [47] developed latent erosion visualization test equipment based on planar laser-induced fluorescence (PLIF) technology and observed the particle movement inside the soil body. However, most of the modeling tests are for homogeneous slopes, which is difficult to adapt to natural slopes with mostly non-uniform media; in addition, it is difficult to control the accuracy of the external environment of the modeling tests in line with the actual situation.

3.1.3. Field Pilot Study

In situ tests are the most accurate and practical research tools in slope stability studies. Li Yaonan studied the rock mass of a slope at a site using an in situ straight shear test to obtain the shear strength parameters of the rock mass and then evaluate the stability of the slope [48]. Wang Guangshuai investigated the feasibility and effectiveness of the electrochemical method for reinforcing soft slopes in open-pit coal mines through on-site reinforcement tests [49]. Liu Dongdong comprehensively used two research methods, field test and numerical simulation, to thoroughly explore the influencing factors of high slope stability during tunnel construction and analyzed the mechanical behavior of anti-slip piles in detail [50]. Shan et al. [51] summarized the manifestations of freeze–thaw landslides on road graben slopes in seasonal permafrost zones through field investigations of engineering geology and hydrogeology.

In view of the complexity and uncertainty of the actual engineering environment, the establishment of an intelligent remote monitoring and warning system has become an indispensable part of the current slope engineering construction. For example, with the help of the monitoring system of real aperture radar, the slope stability can be accurately assessed for risk. These studies and practices have not only enriched the monitoring means of slope stability but also provided strong technical support for engineering construction. However, it is difficult to control the boundary conditions of the field test, the monitoring physical quantities are significantly affected by environmental factors, and the relationship between the engineering properties of the geotechnical body and the slope stability needs to rely on a large amount of data, so how to efficiently and intelligently carry out the field test of the slope is one of the directions of future research and development.

3.2. Theoretical Studies

Since most of the slopes are exposed in the field environment, which leads to an extremely complicated slope destabilization process, how to predict slope destabilization in time and accurately judging the slope destabilization point is the key issue to improve the stability of slopes. With the deepening of theoretical research and long-term accumulation, three types of theoretical research methods are mainly formed: qualitative analysis, quantitative analysis, and uncertainty analysis.

The qualitative analysis method is mainly based on professional experience and engineering common sense, analyzing the slope stability state and slope destabilization factors through geological exploration, which provides an important reference for the subsequent quantitative analysis. Gao et al. studied rocky slope stability with the help of the engineering geological analogy method [52]. However, the engineering geological analogy method requires more engineering experience accumulation and is more specialized and subjective. Liu and Wang [53] analyzed the effect of soil inhomogeneity on permafrost slope characteristics under freeze–thaw cycles using the local average subdivision method. Azarafza et al. analyzed the application of the expert system method in slope failure modeling and assessment [54].

The quantitative analysis method involves quantifying and analyzing the parameters of the slope by establishing an engineering mechanics model and applying the principles of engineering mechanics, so as to derive the specific indexes of slope stability, such as the coefficient of safety [55]. Quantitative analysis methods can provide more data support and more technical support for the construction of slope engineering. In the quantitative analysis method, the limit equilibrium method, as an important quantitative analysis method, is applied by the majority of scholars. The limit equilibrium method is mainly based on the principle of mechanical equilibrium to determine the potential sliding surface of the slope and then obtain a reasonable slope safety coefficient. The main methods of the limit equilibrium method include the Fellenius method, Bishop method, Janbu method, Spencer method, Morgenstem-Price method, and so on. Kalatehjari et al. [56] gave a calculation method for determining the sliding direction, which is able to eliminate the limitations of various methods for calculating the sliding direction and improve the convergence, and this method can be applied in various 3D limit equilibrium methods. Wan et al. [57] proposed a simplified method based on Spencer's method to evaluate the stability of three-dimensional asymmetric slopes. The method assumes that the sliding direction is unique and satisfies the force balance in three directions and the moment balance in two directions, and the computational study of two asymmetric examples concludes that the slope stability will be overestimated if the unique sliding direction is ignored. This shows that the limit equilibrium method is universal in the field of slope stability studies.

The uncertainty analysis method is based on the survey technology to obtain the data of the slope geotechnical body and uses the uncertainty principle and method to calculate the slope stability. Uncertainty analysis includes reliability analysis, fuzzy mathematical analysis, gray system analysis, neural network analysis, genetic algorithm, cluster analysis, machine learning, etc. It is one of the ideal theoretical analysis methods to combine as many slope stability influencing factors as possible. Griffiths et al. [58] analyzed the stability of slopes under different working conditions based on the finite element strength discount method and compared and analyzed the test results with the limit equilibrium method to further verify the feasibility of the proposed method. Li et al. [59] studied and analyzed the stability of rocky slopes based on the Hoek–Brown criterion using the finite element limit analysis method and finally obtained dimensionless slope stability coefficients and safety coefficients.

The above three methods are the most commonly used theoretical research methods at present, but the actual situation of the slope is complex and changeable, and the scope of application and advantages and disadvantages of each analysis method should be fully considered in the process of practical application, as shown in Table 1.

Table 1. The application range and advantages and disadvantages of existing slope stability analysis theory.

Method	Scope of Application	Advantage	Shortcoming
Qualitative analysis [7]	Simple geology	The deformation mechanism can be determined	Empirical and subjective
Quantitative analysis [60]	Single influence factor and simple model	The calculation formula is simple	Errors in calculation results
Uncertainty analysis [61]	When there is uncertainty	More comprehensive analysis	Difficult to accurately determine the probability of each factor

The actual situation of slope engineering is complex and variable, and a single analysis and evaluation method is often difficult to comprehensively respond to the actual problem. Therefore, in the study of slope stability, according to the characteristics and complexity of the specific slope, a variety of analytical methods are used to accurately determine the evolution status and trend of the geotechnical body, so as to improve the stability and safety of slope engineering.

3.3. Numerical Simulation Studies

The numerical analysis method is the mainstream analysis method in geotechnics as compared to the limit equilibrium method. In addition to calculating the stability coefficient of the slope, it can also derive the displacement, strain, and stress distribution of the slope. The advantages and disadvantages of different numerical methods are shown in Table 2.

The finite element method (FEM) is currently the most common numerical simulation method. FEM can effectively deal with the non-homogeneity and discontinuity problems of slopes and realize the equivalent system conversion between infinite and finite degree of freedom structures; FEM is not only excellent in linear analysis but also suitable for nonlinear analysis, which is suitable for almost all computational fields. In addition to this, the method can approximate the critical points where the slope is most susceptible to yielding damage, as well as the need for reinforcement, and simulate the interaction mechanism between the geotechnical body and the supporting structure. Zhang et al. [62] analyzed the stress field distribution pattern during the deformation process occurring in the slope and finally derived the safety factor of the slope. Su et al. [63] analyzed the effect of vibration on high slopes subjected to vibration in staged excavation based on FLAC software (FLAC 1.2.1) and proved that the support works can increase the slope stability under this condition. Wang Rui [64] developed a series of modules based on FLAC3D software (FLAC3D 6.0) Fish language programming from the principle of saturated–unsaturated seepage, including the unsaturated seepage analysis module, unsaturated zone shear strength modification module and rainfall infiltration boundary function module, and used the module to carry out the analysis of seepage and transient stability of saturated and unsaturated slopes in the rainfall process. The analysis method takes into account the influence of seepage in saturated and unsaturated slopes and provides a reference basis for engineering design and construction.

However, there are still some limitations of the finite element method in practical engineering. One of the main problems is that it is very sensitive to the selection of physical parameters, which may have a large impact on the analysis results. In addition, the finite element method also has some difficulties in dealing with problems such as large deformations and stress concentrations, which need to be further improved and optimized. Compared with the finite element method, the boundary element method (BEM) is able to reduce the dimensionality of the problem to be solved, which can model two-dimensional problems into one-dimensional ones and three-dimensional problems into two-dimensional ones [65]. Therefore, the boundary element method has a high solving efficiency. The base variables of the boundary element method are the boundary variables, and all other variables can be obtained by solving the base variables.

The discrete element method (DEM) is an emerging method that has attracted much attention in recent years in the study of slope stability, and it is capable of analyzing the damage mechanism of slopes more accurately. By taking into account the discontinuities and interactions of the rock and soil, the discrete element method is able to simulate the deformation and damage process of the rock and soil in a finer way, and thus, the stability of the slope can be assessed more accurately. Li X et al. [66] used DEM to numerically simulate a homogeneous cohesive soil constituting a slope using contact-bonded graded aggregates with diameters ranging from 80–160 mm to simulate cohesive soils, and investigated microcrack extensions, particle displacements, particle motions, and porosity variations within the slope fill. The simulation results show that the failure mechanism is a rotational mechanism at the beginning stage and gradually changes to a sliding/flow mode as the failure occurs; in addition to this, the sediment porosity increases significantly due to swelling and block voiding. However, it should be noted that there are some challenges in the use of the discrete element method, one of which is the high requirement for the accuracy of the initial parameters and boundary conditions of the geotechnical soil.

Table 2. Advantages and disadvantages of different numerical methods [67].

Numerical Method	Solution Method	Advantage	Shortcoming
Finite element method (FEM)	The stress field and displacement field of rock and soil media are solved using the matrix displacement method or force method	It can be used to solve the problems of elasticity, elastoplasticity, viscoelastoplasticity, and viscoplasticity	The solution is ideal for large deformation, discontinuous displacement, infinite field, stress concentration, and so on
Boundary element method (BEM)	The medium boundary is discretized into boundary elements, the boundary differential equations are transformed into linear algebraic equations, and the boundary stress and displacement solutions are solved	Only the boundaries of the study area are discretized. With less data input, it is ideal for dealing with unbounded and semi-unbounded problems	The fundamental solution of the governing differential equation must be known; it is inferior to the finite element method in dealing with nonlinearity, non-uniformity, and simulating step-by-step excavation
Discrete element method (DEM)	Discrete regions into units; the force between elements is determined by the relation between force and displacement, and the motion of individual elements is determined by Newton’s law of motion	Considering the characteristics of heterogeneity, discontinuity, and large deformation, the blocks can be translated, rotated, and even separated from each other	It is only suitable for rock masses with blocks, stratified fractures, or general cataclastic structures
Unbounded element method	It is widely used to solve nonlinear problems, dynamic problems, and discontinuous problems and is the extension of the finite element method	Effectively solve the “boundary effect” of the finite element and the shortcomings of artificial boundary determination	Generally, it should be combined with other methods, such as the finite element method
FLAC method	Finite difference principle	The characteristics of rock and soil discontinuity and large deformation are fully considered, and the solution speed is fast	The division of the computing boundary and the cell grid has great arbitrariness
Block theory (BT)	Principles of geometry and analytical methods	The geometric features, using the principles of topology and group theory, are suitable for rock mass stability analysis	Only shear strength is considered, regardless of joint deformation and force–moment action

In addition to theoretical frameworks and model development, practical aspects of numerical modeling play a crucial role in the application of slope stability analysis. These considerations include the selection of appropriate software tools, assessment of computational demands, and the treatment of complex behaviors such as large deformations, material heterogeneity, and non-linearity. A range of commercial and academic software platforms is available for slope stability modeling, each offering specific advantages. For example, PLAXIS (V20.0.0.x) and GeoStudio (2021.4) are commonly used for two-dimensional finite element or limit equilibrium analyses due to their user-friendly interfaces and comprehensive material libraries. For more advanced analysis, such as large-strain or dynamic problems, tools like FLAC3D (FLAC3D 6.0)and ABAQUS 2016 provide greater flexibility and control. The choice of software should be guided by the specific requirements of the project, including the type of analysis (static vs. dynamic), dimensionality (2D vs. 3D), and complexity of the geological profile. Soil and rock materials frequently exhibit non-linear stress–strain behavior, particularly under high stress or post-yield conditions. Incorporating advanced constitutive models, such as the Hardening Soil Model, Modified Cam–Clay, or strain-softening Mohr–Coulomb models, is essential for realistic simulations. These models demand accurate parameter calibration, typically based on laboratory or in situ test data, which may not always be readily available. Nonetheless, failure to consider non-linear behavior can lead to significant errors in stability assessments. Incorporating these practical considerations enhances the reliability and applicability of numerical simulations in slope engineering. A well-informed balance between model complexity, computational resources, and available data is essential for effective and efficient slope stability analysis in real-world engineering practice. The correlations among various research methods are shown in Figure 3.

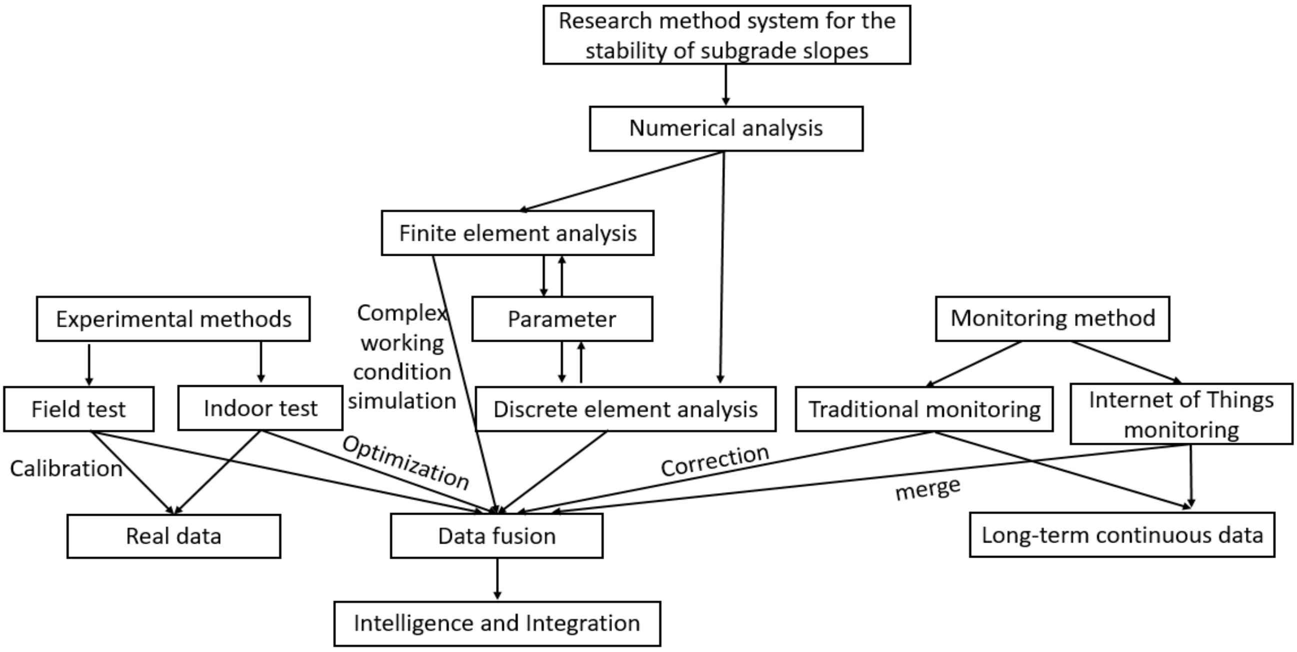

Figure 3. Schematic diagram of the complementarity of research methods.

4. Slope Damage Prevention and Control Measures

The stability of roadbed slopes plays a key role in the safe and smooth flow of highways. However, slope problems occur from time to time, posing a significant threat to highway safety, so an in-depth study of the prevention and control measures of roadbed slopes is of great significance. The prevention and control measures of roadbed slope damage can be divided into two kinds of protection: slope surface protection and slope body protection. Slope protection involves taking vegetation planting or engineering measures to prevent the natural factors caused by slope scouring and deformation damage caused by the slope itself. Slope protection mainly involves enhancing the integrity and stability of the soil body of the roadbed slope as an engineering measure.

4.1. Slope Surface Protection

4.1.1. Vegetation Cover

Vegetation protection involves utilizing the growth characteristics and ecological functions of plants to enhance the stability and erosion resistance of slopes by covering the slopes, fixing the soil, and improving the soil structure [68]. The plant fixes the soil through its root system to reduce rainwater scouring, while plant growth will also play an improvement role in improving soil structure, soil water, and fertilizer retention capacity.

In order to improve the stability, service life, and aesthetics of existing slopes, researchers and scholars have carried out a lot of studies. In the 1950s, the spraying technology of a thick growing base was researched in Japan. Yang et al. [69] simulated the mechanical effect of grass roots by using the unconfined compression test and three-dimensional finite element method study and confirmed that the horizontal fine roots and transverse fine roots played a greater role in reinforced soil than vertical fine roots and that the reinforcing effect of grass roots was better on the upper and middle slopes of slopes than on the lower slopes. Fan et al. [70] found that on steep slopes (greater than 45°), plant roots alone do not provide sufficient shear resistance, so additional stabilization methods are needed to prevent sliding. Okura Y et al. [71] showed that the use of slope protection measures that destroy the natural environment (slurry masonry schist, sprayed cement mortar shoring, etc.) has been abolished in many countries and replaced by the active promotion of slope greening and various flexible slope protection methods, i.e., methods that combine plant measures and engineering measures. Lutz et al. [72] pioneered the study of root ecology and took the root systems of field crops and the root development of vegetable crops as the main research objects.

4.1.2. Engineering Protection

Slope engineering protection is an important measure to ensure the safety and stability of slopes. It involves the application of a variety of technologies and materials, which should be determined according to the geological, hydrological, and climatic conditions of the slope, as well as the construction conditions. The engineering protection of the slope surface mainly involves protecting some weathered soft rocks, and the steep slope surface, which is not suitable for the growth of grass and trees, can be protected by engineering protection methods, such as smoothing, whacking, grouting, hooking (grouting), and slope retaining walls. These methods can form a solid protective layer on the surface of the slope, effectively preventing the loosening and collapse of the slope. The applicable conditions for slope engineering protection are shown in Table 3.

Table 3. Protection for the manual application of slope engineering.

Type	Applicable Condition
Coating protection	Soft rock formation
Mortar or concrete shotcrete protection	Soft rock prone to weathering, lack of slope flatness, and crushing heavy rock slope
Dry piece protection	Slopes susceptible to weathering and severe damage
Slurry masonry revetment	Soil slope that is severely scoured by water
Wall protection	Slopes with soft rock formations or excavated slopes are more broken

4.1.3. Flexible Protection

Flexible protection refers to the reinforcement and protection of slopes using flexible materials such as geogrids and geotextiles. The use of geocells in slope protection allows the water flow rate to be alleviated to a large extent and also avoids the formation of runoff on the slope surface. In addition, the integrity and flexibility of geocells overcome the problems of schist skeleton protection in terms of loosening and caving. Sawangsuriya et al. [73] used different types of materials to improve highway roadbed slopes and obtained geocell-protected slopes with better erosion prevention characteristics. Mehdipour et al. [74] investigated the effect of slope geometry, shear strength characteristics and soil compaction on geocell-reinforced slope protection through numerical simulation, and the results of the study showed that, when the geocell layer fabric was set up in the middle of the slope and in the middle of the critical damage surface of the unreinforced slope, the highest safety coefficient was obtained when the ratio of the length of the geocells to the thickness of the geocells was 2 and the gradient of the geocells was 60°. Wang De-yong et al. [75] conducted an erosion resistance study of berms using geocells of degradable materials, and the results showed that the geocells of this material were able to reduce the maximum water erosion by more than 10%, and furthermore, the maximum water erosion could be reduced by about 20% compared to the un-reinforced bare slopes in the case of strong precipitation. Suraj Vedpathak et al. [76] carried out the design of geocell vegetated slope protection for slopes with severe soil erosion and proposed a new calculation method and construction process.

4.2. Slope Protection

4.2.1. Retaining Walls

Retaining walls as a support for roadbed fill or hillside soil, to prevent fill, soil deformation and instability, landslide, or collapse of engineering structures, are significantly affected by earthquake effects. Classified by structural form, retaining walls can be mainly divided into gravity retaining walls, thin-walled retaining walls, reinforced soil retaining walls, anchor-rod retaining walls, anchored plate retaining walls, vertical prestressed anchor retaining walls, soil nail retaining walls, pile-and-slab retaining walls, and other types. In general, there are various types of retaining walls, and the choice of which type of retaining wall to choose needs to be based on specific engineering conditions, geological conditions, environmental factors, and economic factors for comprehensive consideration [77].

Nadim and Whitman [78] analyzed the motion of a retaining wall, considering the amplification effect of vibration in the fill behind a gravity retaining wall, using the finite element method. The acceleration at the top of the fill (3.125 H from the wall), the total dynamic earth pressure on the retaining wall, the shear force at the base of the wall, and the time course of the dynamic displacements (including permanent displacements) were computed for different frequencies in sinusoidal form, as well as for three actual seismic records as inputs. Buklje L et al. [79] investigated the effect of creep action on lateral pressures in cohesive soils and showed that in certain clays, the retaining wall moves slowly outward for a long period of time, and if this deformation is prevented, the lateral pressures will gradually increase until they approach the static earth pressure. Buklje L et al. [79] performed elasto-plastic finite element analysis of active and passive earth pressure problems on rigid retaining walls and proved that the distribution of earth pressure acting on rigid retaining walls is related to the dislocation mode of the retaining wall and that the value of the total earth pressure and the point of action of the combined earth pressure force acting on the retaining wall are related to the friction characteristics of the wall surface, the mode of wall dislocation, and the displacement of the wall and that there is a nonlinear relationship between the magnitude of the earth pressure and the displacement of the wall. Fathipour et al. [80] used the limit analysis lower limit finite element method to analyze the soil pressure of retaining walls under unsaturated steady state seepage conditions and explored the effect of different parameters on soil pressure under unsaturated conditions. Fan et al. [81] modeled a rigid retaining wall using the finite element software PLAXIS (V20.0.0.x) and analyzed the effects of aspect ratio and friction angle of the fill behind the wall on the active earth pressure coefficient and the location of the active earth pressure ensemble. tom Wörden et al. [82] employed ABAQUS 2016 to study the three-dimensional active earth pressure in sandy fill and compared the results obtained from numerical simulation with those from model tests to verify the accuracy of the numerical model.

In addition, for the reinforced retaining wall, after analyzing through numerical simulation, Wang Yimin et al. [83] found that the lateral displacement of geogrids and panels of the reinforced retaining wall increased due to the increase in the seismic duration, and the effect of seismic time duration on the resistance and deformation of the reinforced retaining wall was stronger. Lou Huafeng et al. [84] established a numerical model of reinforced retaining walls based on FLAC3D and analyzed the effect of wall inclination on lateral deformation, earth pressure, and reinforcement tension of modular reinforced retaining walls and found that 75° is the inflection point of the deformation of modular reinforced retaining walls affected by the strength of the inclination of the wall, and when the inclination of the wall is less than 75°, the continual decrease in the inclination of the wall will not bring about a significant decrease in the deformation of the retaining wall.

4.2.2. Slope Stabilization

(1) Anchor (cable) protection

If the slope is a hard rock, which has a broken structure or a stratum with discontinuous laminar structure, it is advisable to adopt the anchor rod (cable) technique to prevent rock fracture. C. A. Stamatopoulosa [85] conducted centrifuge model tests on slopes supported by anchors and suggested the application of the anchor support method in seismic engineering of slopes by analyzing the response law and deformation characteristics of slopes under dynamic loading. N. Ma et al. [86] used a large shaking table test to comparatively study the dynamic response of slopes supported by pile–anchor structures and pile–beam structures under seismic action, and through the analysis of acceleration spectra and displacement spectra of the slopes, they came to the conclusion that the pile–anchor structure has better dynamic slope fixing effects. Chen WF et al. [87] introduced compliant geotechnical materials into Hoek–Brown's nonlinear damage criterion based on the limit analysis upper limit theory, so as to calculate the optimal solution algorithm for critical yield acceleration of anchored slopes.

(2) Soil nail support

Some soil slopes will be supported by soil nails, the principle of which is basically the same as that of anchor (cable) protection, by driving soil nails into the soil body, so as to enhance the anti-slip capacity of the soil body and ensure the good stability of the soil body. C. Thomas et al. [88] conducted a numerical simulation based on a soil nail wall support structure, and concluded that the change in the cohesion and elastic modulus of the soil body has a significant effect on the deformation of the foundation pit. Emanuele [89] developed a non-metallic glass fiber-reinforced polymer soil nail and applied it to a long river embankment in the Netherlands. Carlos et al. [90] investigated the puncture resistance, tensile properties, and water permeability of geotextiles under loading and further evaluated the mechanical damage of the geotextiles by performing repeated loading tests on flexible face geotextiles. Ahmadi et al. [91] concluded that the maximum soil nail resistance generally occurs at a certain distance behind the wall by means of soil nail wall model scaling tests.

(3) Skid pile

A slope anti-slip pile is a kind of support structure installed on the surface or inside of the slope, and its function is to increase the stability of the slope. Yang et al. [92] established a new model of the h-type anti-slip pile based on the Winkler foundation model, and found that compared with an ordinary anti-slip pile, the top displacement of the h-type anti-slip pile is 41.4% smaller than that of an ordinary anti-slip pile with the same cross-sectional area, and further parametric analysis shows that increasing the width of the pile can significantly reduce the top displacement of the h-type anti-slip pile. Sawwaf et al. [93] analyzed the force and deformation characteristics of sandy soil slope loaded at the top of the slope based on a small-size model and found that the anti-slip piles can effectively improve the bearing capacity of the slope; in addition, it was also found that the pile spacing and the depth of burial of the piles have a greater effect on the stability of the slope than the diameter of the piles. S. Yang et al. [94] found that with the increase in anti-slip pile length, the influence parameter also changes, which further improves the bearing capacity of the soil body.

In summary, roadbed slope damage is jointly influenced by a variety of factors, which interact and influence each other, constituting a complex system of slope stability. In future research and practice, these factors need to be considered comprehensively, and comprehensive measures need to be taken to effectively prevent and control the occurrence of roadbed slope damage. The comprehensive system diagram of prevention and control measures is shown in Figure 4.

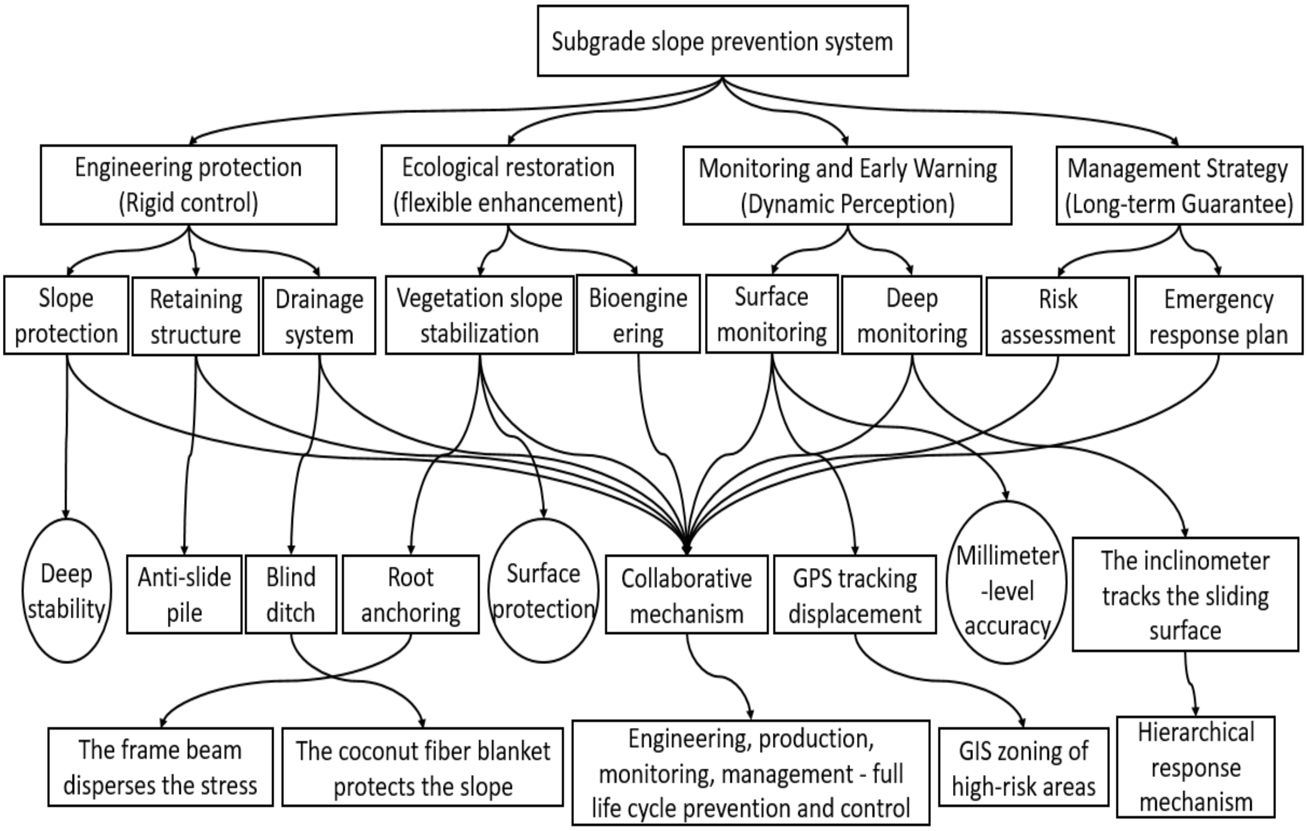

Figure 4. Comprehensive system diagram of prevention and control measures.

5. Conclusions and Outlook

The study of slope stability is a long-term research topic in order to prevent disasters caused by slope damage. Obviously, the research discussed in this paper is only the beginning stage of a long road to provide final, complete, and valuable slope stability research, for which we still need to make great efforts. By reviewing the existing studies and synthesizing and analyzing the roadbed slope stability studies, the following main conclusions are drawn:

(1) Slope damage is the further development of slope deformation. The form of damage has been basically clear, mainly divided into landslide, avalanche, collapse, and spalling four forms. While these categories have been clearly established, future research

should focus on deeper investigations into the triggers, behaviors, and interactions of these forms of damage to better predict and prevent their occurrence in varying environmental and geological conditions.

(2) Among the current research methods, field testing remains the most reliable and representative, yet it is also the most resource-intensive. Emerging technologies such as sensor networks, remote sensing, and AI-driven monitoring systems offer promising avenues for developing smart, real-time field testing platforms. Additionally, due to the inherent complexity of slope systems, coupled theoretical models (e.g., FEM–DEM and hydro-mechanical–thermal models) will increasingly dominate future research. These approaches should aim to integrate data across scales and disciplines.

(3) Slope stability is affected by both internal and external factors. how to analyze the coupling mechanism of internal and external factors and realize the decoupling of the coupling effect is the key point of slope stability research. Research should prioritize the development of integrated models that better capture the interaction between these factors, potentially through interdisciplinary approaches combining geology, geotechnics, and environmental sciences.

(4) The prevention and control of slope damage is carried out from two aspects: the slope surface and the slope body. Considering that the slope damage is caused by the coupling of many factors, future research on the prevention and control measures of slope damage should consider comprehensive prevention and control measures.

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