Review on Research Progress and Application of Reinforced Soil

Meng Cui¹², Linna Hu¹*, Xiao Fu¹ and Hailin Liu³

¹College of Civil and Structure Engineering, Nanchang Institute of Technology, Nanchang, 330099, China
²Key Laboratory of Hydraulic and Waterway Engineering of the Ministry of Education, Chongqing Jiaotong University, Chongqing 400074, China
³China Nerin Engineering Company Limited, Nanchang, 330031, China
Email: 864909285@qq.com

Abstract. Reinforced soil structure is particularly popular in the field of construction engineering because of its remarkable social, economic and environmental benefits, and is one of the current research hotspots. As a new type of geotechnical structure, reinforced soil has its mechanical characteristic affected by various complex factors, such as the type of reinforced material, the length of the reinforced material, the spacing between the reinforcements, the water content, the drawing directions, the earthquake, the traffic load and so on. Based on studying papers and books, this paper expounds the structural strength characteristic, the interface characteristics and stability of reinforced soil from three aspects, which include basic theory, experimental research and numerical analysis, and the applications of reinforced soil structures in geotechnical engineering are listed. Finally, in view of the current research status and development trend of reinforced soil, the focus and direction that need further research in the future are put forward.

Keywords. Reinforced soil, strength, interface characteristics, stability, application.

1. Introduction
The soil has certain compressive and shear strength, but it cannot bear tensile force. Therefore, by adding tensile materials to the soil, the compressive strength of the soil is linked to the tensile strength of the reinforced material through friction resistance, so as to enhance the strength and stability of the soil [1]. This kind of soil with reinforced material is called reinforced soil. As early as the reign of Emperor Wudi of the Han Dynasty, the engineering application of reinforced soil structure was established in China. However, the concept of modern reinforced soil structure was proposed by Henri Vidal, a French engineer, in the 1960s, and the reinforcement method and design theory of soil was established for the first time [2]. Up to now, the reinforced soil structure has been widely used in engineering such as reinforced soil retaining walls, reinforced soil slopes and other engineering by virtue of its good reinforcing effect and engineering applicability.

2. Basic Theory of Reinforced Soil
According to the research results so far, the basic theory of reinforced soil can be roughly summarized into two types: friction reinforcement theory and pseudo-cohesion theory.
2.1. Friction Reinforcement Theory

The friction reinforcement theory [3] holds that in the reinforced soil structure, the earth pressure generated by the weight of the filling soil and external force is transmitted to the reinforced material through the connecting parts of the wall panel, which makes the reinforced material produce tension. At the same time, the reinforced material is subjected to the pressure of the filling soil, so the friction between the filling soil and the reinforced material prevents the reinforced material from being pulled out. Therefore, as long as the reinforced material has sufficient strength and produces enough friction resistance with the soil, the soil can remain stable.

A micro segment is taken from the reinforced soil for analysis, as shown in figure 1. The length of the micro section is \( dl \). The forces on the left and right sections of the reinforcement are \( T_1 \) and \( T_2 \) respectively. The normal stress acting on the reinforced material is \( \sigma \). Suppose the friction coefficient between the reinforced material and the soil is \( f \). The width of the reinforced material is \( b \).

The tensile force caused by the horizontal thrust of soil in the micro segment is:

\[
dT = T_1 + T_2 \tag{1}
\]

The total friction force generated by soil and reinforced material on the micro segment is:

\[
dF = 2\sigma f bd\!l \tag{2}
\]

According to the force analysis of the micro segment, if \( dF > dT \), there will be no mutual dislocation between the reinforced material and the soil, that is, the micro unit can remain stable.

![Figure 1. Theory of friction reinforcement.](image)

2.2. Pseudo-cohesion Theory

The pseudo-cohesion theory [3] believes that the reinforced soil structure can be regarded as anisotropic composite material. The elastic modulus of the commonly used reinforcement material is much higher than that of the filling soil. The strength of the reinforced soil is significantly improved due to the joint action of the reinforced material and the filling soil. The basic stress state is shown in figure 2.

![Figure 2. The basic stress state of unreinforced soil and reinforced soil](image)

![Figure 3. Strength analysis of unreinforced and reinforced sand samples](image)
In the triaxial comparison test between the unreinforced sand sample and the reinforced sand sample, if the unreinforced soil reaches the limit equilibrium under the action of the maximum principal stress $\sigma_1$ and the minimum principal stress $\sigma_3$, as shown in figure 3(a). Then the reinforced sand sample cannot reach the limit equilibrium under the same stress, as shown in figure 3(b). If $\sigma_1$ remains unchanged, to make the reinforced soil reach a new limit equilibrium, $\sigma_1$ must be increased to $\sigma_1f$, as shown in figure 3(c).

The reinforced material does not break or slip, only the sand soil is damaged. The internal friction angle $\varphi$ of the sand sample before and after reinforced is basically similar, and the failure envelope of the reinforced sand sample does not pass through the origin of the coordinate, and its intercept is $c$. Hence, it can be seen that the strength increase of the reinforced soil is equivalent to an increase of cohesion force $c$.

The ultimate strength of the soil is:

$$\tau_f = \sigma t a \varphi + c$$  \hspace{1cm} (3)

The mathematical expression of the sample under the new equilibrium state:

$$\sigma_{1f} = \sigma_3 \tan^2(45^\circ + \varphi / 2) + 2c \tan(45^\circ + \varphi / 2)$$  \hspace{1cm} (4)

If the reinforced sand sample is regarded as an unreinforced sand sample, the corresponding $\sigma_3$ is replaced by $\sigma_3 + \Delta \sigma_3$. When it reaches the limit equilibrium state, then:

$$\sigma_{1f} = (\sigma_3 + \Delta \sigma_3) \tan^2(45^\circ + \varphi / 2)$$  \hspace{1cm} (5)

From formulas (4) and (5), $c = \Delta \sigma_3 \tan (45^\circ + \varphi / 2) / 2$ is obtained, which is the cohesive force increased by the reinforced soil, that is, the pseudo-cohesion.

3. Experimental Research

3.1. Research on Strength Characteristics of Reinforced Soil

Since modern reinforced soil technology was proposed, scholars have been committed to the research of different reinforced materials in different fillings [4-5]. The reinforced materials include fiber, geogrid and so on, and its filling is mainly sandy soil and cohesive soil. There are many factors affecting the strength and performance of reinforced soil, and triaxial test is the most important method to study the strength characteristics of reinforced soil.

Lei [6] studied the influence of the number of reinforced layers on the strength of reinforced soil. On this basis, Xie et al. [7] concluded that it is not the more reinforcement layers, the more conducive to soil stability, but there is an optimal reinforcement location and layer spacing, which can significantly improve the strength of reinforced soil. Wang et al. [8] compared the strength changes of reinforced soil with different reinforced materials and the corresponding plain soil before and after reinforcement, and concluded that inaccurate reinforced material selection may lead to adverse consequences of the project. Estabragh et al. [9] introduced nylon fiber into the soil and analyzed the influence of the fibrous material on the properties of the clay. Wang et al. [10] studied the influence of different fiber content and length on the strength of reinforced soil, and found that there was an optimal content and length value to make the soil strength the highest.

3.2. Study on the Interface Characteristics of Reinforced-soil

The interface characteristics between reinforced material and soil reflect the reinforcing effect of reinforced soil structure, and will directly affect the safety and stability of reinforced soil structure [11]. The reinforced-soil interface characteristic test is the most important way to study and reveal the force and deformation laws of the reinforced-soil interface. At present, the most common and effective test methods for the properties of the reinforced-soil interface mainly include direct shear test and the pull-out test.

Scholars focused on the variation rules of the properties of the reinforced-soil interface under different conditions, such as stress, grain composition and water content, and obtained a series of
conclusions with reference value [12-13]. Wang et al. [14] studied the influence of the relation between soil moisture content and optimal moisture content on the reinforced-soil interface, and proposed that when the difference between the two is within ±3%, the cohesive force and shear strength between reinforcement and soil interface are the largest. Lee et al. [15] studied the influence of boundary conditions and test methods on the results of the reinforced-soil interface characteristics. At the same time, shear speed and displacement also affect the properties of the reinforced-soil interface [16-17]. Cai [18] divided the pull-out test process of the reinforced-soil interface into three stages, and pointed out that there were obvious differences in the mechanical properties between the stages. Cao and Zheng et al. [19-20] studied the influence of 0° and 90° drawing directions on the deformation characteristics and the properties of the reinforced-soil interface of the three-way geogrid.

4. Numerical Analysis

In the calculation and design methods of reinforced soil structures, most methods such as the limit equilibrium method and limit analysis method are used to analyze its stability. However, these stability methods based on the limit equilibrium theory ignore factors such as the coordinated deformation of reinforcement, soil and other structures, which often lead to a large difference between the calculation results and the actual results [21-22]. Numerical analysis can solve the above problems. The most commonly used numerical analysis methods are the finite element method and the discrete element method. The numerical analysis software has PLAXIS, FLAC, PFC and so on.

4.1. Finite Element Method

The finite element method can analyze the displacement, strain and deformation failure laws of the reinforced material in soil, simulate the test process, and process the test data. Cao et al. [23] compared geocell reinforced cushion with geogrid reinforced cushion and found that the former could significantly reduce the settlement between piles and the settlement between pile-soil. Li et al. [24] studied the influence of compaction stress on reinforced soil retaining wall and pointed out that the influence of compaction stress will dissipate only when the additional load of retaining wall exceeds the compaction load. Zheng et al. [25] compared with the numerical model of reinforced soil retaining wall without EPS plate, the influences of soil pressure and horizontal displacement of composite retaining structure, pile horizontal displacement and bending moment were analyzed.

4.2. Discrete Element Method

The discrete element method can analyze the behavior of granular materials well, solve the problems that finite element method is difficult to reflect in the mechanical mechanism, such as the rotation of soil particles [26-27]. Gao [28] established a numerical model of the sand pebble filling reinforced soil retaining wall through PFC 2D, studied the stress state of the vertical reinforced soil retaining wall under the top load and the displacement law of the filling in the wall, analyzed the failure mechanism of reinforced earth retaining wall, determined the potential fracture surface of the retaining wall. Zheng et al. [29] used PFC 3D to establish a reinforced soil pull-out test model, simulated sand particles through the “clump” method, and studied the microstructure evolution of the reinforced-soil interface and the influence of soil particle size on the reinforcement effect. Wang [30] simulated the instability and failure dynamic process of the stepped reinforced soil retaining walls, analyzed the distribution characteristics of soil particle displacement, stress and force chain structure of reinforced soil retaining walls.

5. Application of Reinforced Soil in Geotechnical Engineering

Since the advent of reinforced soil technology, it has been widely used in geotechnical engineering. It provides support for retaining walls, bridge abutments and other projects, applied to embankment, foundation reinforcement and other stabilize soil structures projects [31-32].

Yang et al. [33] conducted a systematic test on a highway reinforced soil retaining wall, analyzed the influence of filling height on the earth pressure at the back of the wall and the displacement of the
reinforced material. For the construction of reinforced earth Shenshan railway span bridge abutment, Zhang [34] explored the design theory, structural form and construction technology of the built, through the static load test and the overall deformation observation verifies the reliability of the research results and the overall safety. Hao [35] compared the numerical model with the measured data of the embankment wall, studied the influence of different embankment filling heights and high-speed trains on the embankment-type reinforced soil retaining wall.

6. Conclusion

In recent years, domestic and foreign scholars have explored the factors affecting the structural characteristics of reinforced soil through experiments and numerical analysis, which play a positive role in improving the theory and standard design methods of reinforced soil engineering, and promoting the wider application of reinforced soil technology in construction projects. According to the current development trend of reinforced soil, the main issues to be further studied include:

(1) A lot of achievements have been made in the study of properties under static action, but in practical engineering, reinforced soil structures may be subjected to dynamic actions such as earthquake and traffic load. Consequently, the study of reinforced soil structure under complex environmental dynamic load needs to be improved.

(2) The practical problems solved by various tests and numerical simulations are relatively single, and because the equipment and methods used by the researchers are inconsistent, the results are different and the comparability is not strong. Therefore, it is necessary to formulate relevant standards.

(3) Although reinforced soil structure is widely used, there is no reliable theoretical analysis basis to guide the design, and the theory of reinforced soil falls behind the practical application of engineering. The research on reinforced soil theory still needs to be strengthened.

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