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Application and Research Progress of Filling Piles in Expansive Soil Foundation

Xu Yang[1,a,*]

Nanjing Hydraulic Research Institute, No.34 Huju Pass, Nanjing, China
**Corresponding author: 191622836@qq.com*

Abstract: *Expansive soil is a type of clayey soil with a unique expansion structure, which exhibits two deformation characteristics: significant water absorption and expansion, and water loss and contraction. This soil type often poses a serious threat to engineering construction. Filling piles offer several advantages, including wide adaptability, convenient construction, no vibration, and no crowding. Therefore, it is a safe and reliable method for dealing with expansive soil foundations. This paper summarises the application and research progress of filling piles in expansive land foundation, as well as the shortcomings of the existing research, to provide a theoretical basis for subsequent research.*

Keywords: *Filling piles; Expansive soil foundation; Single pile bearing capacity; Pile-soil interaction*

1. Introduction

Expansive soil is an unsaturated soil that contains hydrophilic mineral components. It has significant water absorption and expansion characteristics, as well as water loss contraction deformation characteristics. It is very sensitive to changes in the climate. Under dry and wet cycles, the soil experiences repeated expansion and contraction, which leads to a sharp decline in strength and can cause the soil to disintegrate. This can be harmful to various types of engineering shallow surface layers with lightweight structures. This type of destructive effect can pose multiple and repeated long-term threats to various engineering fields.

In the construction of civil engineering projects such as railroads, highways, water conservancy projects, buildings and so on, the problem of expansive soil is often encountered. Pile foundation is an important form of foundation widely used in modern civil engineering. Filling pile has the advantages of wide adaptability, convenient construction, no vibration, no crowding, etc., which is a safe and reliable method to deal with expansive soil foundation. In order to minimize the effect of soil swelling due to water expansion and cause the uplift of structures, the foundation of structures often adopts the pile foundation form, and the pile base is generally located on the non-expansive soil layer. However, due to the complexity of expansive soils, improperly designed pile foundations in expansive soils are likely to generate large uplift forces on the foundation piles due to the vertical expansion forces of the expansive soils around the piles, which in turn affects the safety of the structures above the foundation piles. Therefore, the study of the interaction between foundation piles and expansive soil in expansive soil foundation is of great practical importance.

2. State of expansion and constitutive modeling of expansive soils

2.1 Study of the expansion and contraction of the expansive soils

Engineering problems arising from the expansion and contraction characteristics of expansive soils have been the concern of scholars at both national and international levels. The embankments, foundations and retaining walls of railways, highways, tunnels and buildings are all at risk from expansive soils, and the cost of repairing them is enormous.

Expansive soils are composed primarily of clay minerals, such as montmorillonite and illite. These minerals cause the soil to expand when absorbing water and contract when losing water. Scholars at home and abroad have conducted extensive research on the expansion and contraction mechanism of the theoretical study. This research can be summarized into three categories[2][3][4][5][6]: According to mineralogical theory, mineral lattice structure of clay minerals and cation exchange on surface of particles determine its expansion and contraction; According to physicochemical theory, interaction of water-binding layer on surface of clay minerals and diffusion of double layer affect its expansion property;

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According to physicomechanical theory, interaction of clay and water produces a physicomechanical effect that leads to its expansion. The physico-mechanical effects resulting from the interaction between clay and water cause it to swell.

At present, experts and scholars have studied the causes, distribution, physical and chemical properties of expansive soil, and used different theories and methods to explain and demonstrate the engineering properties of expansive soil. However, the accurate expression of the correlation with expansive soil through the easily measured parameters of expansive soil remains to be further studied as Figure 1.

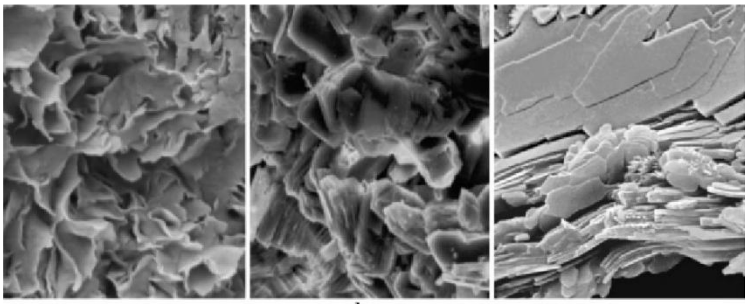

Figure 1:The SEM images of the three typical clay minerals[1]

2.2 Development of constitutive models for expansive soil

As a typical unsaturated cohesive soil, the development of unsaturated soil mechanics provides a good theoretical foundation for the in-depth study of expansive soils.

In 1990, Alonso[7] et al. proposed the Barcelona Basic Model (BBM) for unsaturated soils, which became a classic in the field of unsaturated soil elastoplasticity. Subsequently, Gens[8] and Alonso et al. proposed the Barcelona Expansive Model (BExM) based on the BBM model for expansive unsaturated soils, which is also the earliest constitutive model applicable to expansive soils. Since then, many scholars have also established corresponding constitutive models for expansive soil problems in certain regions.

Lu Zaihua[9] et al. proposed an elastoplastic model for undisturbed unsaturated expansive soil based on triaxial tests. This model is an improvement of the BExM constitutive model. Cao Xueshan[10] et al. analyzed the characteristics of expansive soil based on the BExM expansive soil model, which has the disadvantage of difficult to determine microstructural parameters, and studied the micro-deformation mechanism of expansive soil based on the dry-wet cycle experiment of expansive soil. Eduardo Rojas[11] et al. extended the Alonso constitutive model in 2006.

Table 1:Development of constitutive models for expansive soil.

scholar	Constitutive model of expansive soil	The content
Alonso	BBM model	The basic theoretical framework of the constitutive relationship of unsaturated soil based on the modified Cambridge model.
Gens and Alonso	BExM model	From the macroscopic and microscopic perspectives, the plastic deformation of soil is described, which is applicable to highly reactive expansive soils.
Lu Zaihua	Improved BExM model	An elastic-plastic model for undisturbed expansive soils is proposed, in which an expansion function is introduced to calculate the elastic body deformation increment when the suction decreases.
Cao Xueshan	Improved BExM model	It is believed that the macroscopic swelling-shrinkage plastic deformation of expansive soils is composed of two parts of plasticity, one is the micro-macro structural coupling deformation formed by the coupling of aggregate swelling-shrinkage deformation in the microscopic structural level, and the other is the macroscopic structural plastic deformation.
Eduardo Rojas	Improved BExM model	Based on the research of Gens and Alonso on the inflation yield line, the edge endpoint of the yield surface at the saturated state of expansive soil is shifted to the right, and an E-expansion parabolic yield line is defined.

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Shen Zhujiang model is an elastoplastic constitutive model with double yield surfaces proposed by Shen Zhujiang in the 1990s based on Duncan-Chang model. The model uses volume yield surface and shear yield surface to describe the yield characteristics of soil. The model is simple in form and easy to determine the parameters, so it is widely used in practical engineering. The limiting water content is one of the sensitive indicators reflecting the interaction between soil particles and water. It reflects the hydrophilic property of soil to a certain extent, and indirectly reflects the swelling and shrinking property of expansive soil. Generally speaking, expansive soil is a cohesive soil with high plasticity and high shrinkage. The higher the liquid limit, the lower the shrinkage limit, and the greater the shallow potential of soil expansion and contraction. At present, there are few studies on the moisture content of expansive soil and the parameters of Shen Zhujiang model, which has guiding significance for practical engineering application.

3. Research on the bearing capacity characteristics of filling piles

3.1 Research status of vertical bearing capacity of single pile in expansive soil foundation

Pile foundations in expansive soils often experience additional internal forces and deformations due to changes in the water content in the soil. When the water content in the soil increases, the soil exerts a considerable uplift force on the pile due to the swelling effect of the soil. When the water content in the soil decreases, the soil exerts a downward drag force on the pile due to negative friction that occurs during soil shrinkage or consolidation.

Chen Fu Hua[12] investigated thousands of expansive soil foundation construction sites in the Rocky Mountains, collected a large amount of relevant data, and combined with years of experience in expansive soil foundation construction. He proposed the design theory of various foundations such as expansive soil site foundation, independent foundation, raft foundation, and pile foundation, as well as the corresponding construction methods. Collins proposed an empirical formula for the negative tensile force of piles in expansive soil in 1953. Through the empirical formula for negative tensile force, the internal force at a point of the pile foundation can be calculated, but the settlement deformation of the pile foundation in expansive soil cannot be calculated. Sorochan[13] proposed a design and calculation method for the relative upward sliding displacement of the pile shaft under the combined action of cohesion and external load along the pile shaft in expansive soil through a large number of field tests. Poulos[14] proposed the role of the swelling force of expansive soil based on the external load diffusion angle transfer method and established an elastic force analysis theory. In terms of finite element analysis of the internal force of piles, Ellison[15] analyzed the relationship between the load and settlement deformation of bored piles with diameters between 250mm and 800mm by using finite element method to analyze a typical expansive soil model of London clay. Amir[16] and Sokolov established an axisymmetric stress model by using finite element method to further study the stress-strain relationship of bored piles in expansive soil, so as to study the mechanical characteristics and settlement deformation of pile foundations. Lytton[17] established a finite element model for the stress-strain of pile shafts in expansive soil, and calculated the strain and stress of bored piles. Justo[18] established a two-dimensional finite element stress-strain model for bored piles by using finite element plane analytical method to analyze and solve the stress and strain of pile shafts in expansive soil.

The above methods are basically based on the assumption that expansive soils are homogeneous linear elastic bodies. Therefore, Mohamedzein[19] assumed that when analyzing the behavior of bored piles in expansive soils, the bored pile shaft is a linear elastic deformation body. He established a nonlinear deformation model for expansive soils and analyzed the characteristics of short piles with pile shaft lengths up to 6 meters in expansive soils using finite element analysis.

3.2 Research status of horizontal bearing capacity of single pile in expansive soil foundation

Previous research work has mainly focused on vertical loaded piles, while research on horizontal loaded piles is relatively lacking. In practical engineering, pile foundations subjected to horizontal loads are common, such as earthquake engineering, dock engineering, foundation pit engineering, slope engineering, etc. Therefore, horizontal load is one of the key factors to be considered in the design of pile foundations. The key to the study of horizontally loaded piles is to calculate the deformation and internal forces of the pile shaft. Currently, most research on the relationship between horizontal displacement of the pile shaft and soil reaction force is used to determine the deformation and internal forces of the pile shaft.

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Extensive research has been conducted on the distribution of horizontal soil resistance along depth at home and abroad, and many research results have been achieved.

Rase[20] assumed in 1936 that the reaction force was linearly distributed along the depth. Subsequently, Okabe[21] proposed a different linear distribution form of the reaction force in 1951, and Broms[22][23][24] proposed a parabolic distribution form of the reaction force in 1964. The Japanese Port Structures Design Standards (1968) assumed that the reaction force of soil was randomly distributed along the depth, and proposed the deflection curve method. Chang Youling[25] proposed the constant method in 1937, assuming that the coefficient of reaction force of foundation is constant along the depth, and obtained analytical solutions for the deformation and internal forces of long piles under horizontal load. These methods are summarized as m method, C method, K method, and constant method. Based on the above four research methods, subsequent scholars conducted a series of theoretical and experimental studies on horizontal loaded piles, and achieved fruitful results.

The basic idea of the p-y curve method is to treat the horizontal bearing as a nonlinear Winkler foundation beam, and divide the pile foundation into several small segments along the vertical direction. The relationship between the pile-surrounding soil resistance and the horizontal displacement corresponding to each segment is represented by a curve, which is called the p-y curve. After obtaining the p-y curves at different positions along the pile, the internal forces and deformations of the pile can be calculated by numerical methods. Although the p-y curve method does not consider the continuity of soil deformation, practice has shown that the calculation results of this method are still within a reasonable error range compared to the measured results. In addition, compared to the nonlinear elastic foundation reaction method, the p-y curve method has a simple form and convenient and fast calculation, which is more suitable for solving large deformations of horizontal loaded piles. Therefore, the p-y curve method has become the most commonly used method for solving horizontal loading problems as Figure 2 and Figure 3.

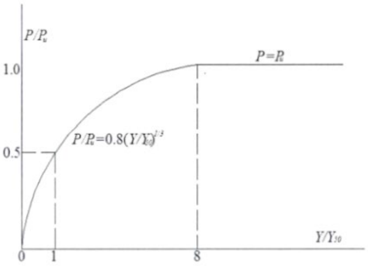

Figure 2:The p-y curve of Matlock' method

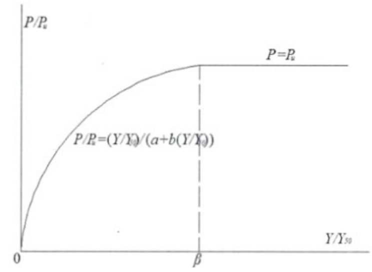

Figure 3:The p-y curve of new uniform method by Hohai University

4. Research on pile-soil interaction

The bearing capacity of pile foundations mainly depends on the pile tip resistance and lateral friction resistance, of which the physical and mechanical properties of the soil mass on the pile side and the interaction between the pile and the surrounding soil determine the exertion of lateral resistance. The main theories for analyzing the interaction between pile and soil include: elastic theory method, load transfer method, shear displacement method, and finite element method.

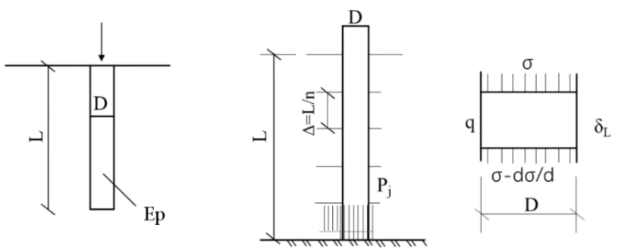

Figure 4: Schematic diagram of friction pile analysis

The elastic theory method was first proposed by Poulos[26] and others in 1968. Subsequently, in 1980, Poulos summarized and concluded the theory and application of this method. The basic assumption of the elastic theory method is that the pile is placed in an ideal homogeneous and isotropic elastic semi-

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infinite body, and the elastic modulus and Poisson's ratio of the soil surrounding the pile do not change due to the presence of the pile. At the same time, it is assumed that there is no relative displacement between the pile and the soil surrounding the pile, that is, the displacement of the pile and soil is coordinated as Figure 4.

The load transfer method was first proposed by Seed[27] and Reese in 1957. The principle of this method is to discretize the pile into many basic units, each of which is connected to the soil with nonlinear springs. The relationship between the force and displacement of these nonlinear springs represents the relationship between the pile side friction and pile tip resistance and the relative displacement of the pile and soil, as shown in Figure 5, which is commonly referred to as the load transfer function. However, the displacement of any point on the pile shaft is only related to the shear stress at that point, and is independent of the stress at other locations on the pile shaft. The deficiency of this method is that it fails to consider the continuity of the soil. In response to this deficiency, domestic scholars have proposed a series of improved methods based on theoretical knowledge and practical experience. Cao Hanzhi[28] proposed the equivalent method of pile tip displacement; Pan Shisheng[29] proposed using a layered displacement iteration method to solve single piles, and extended this method to the analysis of group piles; Chen Rugui[30] proposed the concept of elastic-plastic pile-soil body for load transfer of single piles, based on which a method for practical engineering applications was developed.

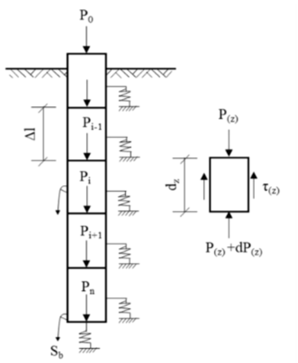

Figure 5: Calculation mode of pile load transfermethod

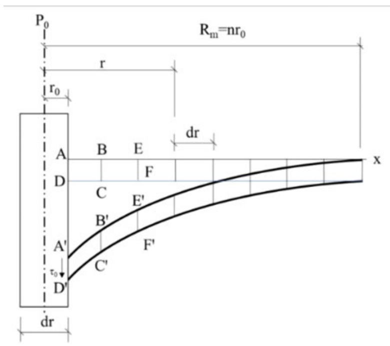

Figure 6: Shear deformation transfer method pile loadtransfer model

The shear displacement method was first proposed by Cooke[31] et al. in 1974, and has since been further studied by Randolph[32], Wroth, Cooke[33], and others to form a theoretical system of shear displacement methods. Yang Rongchang[34] et al. established a generalized shear displacement method and gave an analytical expression for the soil around the pile in a nonlinear displacement field. Compared with the elastic theory method, the shear displacement method introduces a transformation matrix in the vertical direction, which can consider the situation of layered foundation soil. For homogeneous soil, it does not require discretization of the pile, which greatly reduces the computational workload. Wang Dongdong[35] and Sun Jun believe that in the calculation of shear deformation, the pile-soil-cap deformation is coordinated, and this is extended to the calculation of pile top settlement changes over time for pile group foundations as Figure 5.

Courant[36] proposed a stress solution based on variational form in 1943, and since then, numerical simulation methods based on pile-soil interaction have become the main means for analyzing the ultimate bearing capacity of pile foundations (Figure 6). In 1999, Zhang Yongmou[37] and Yang Min established a numerical simulation analysis method for the bearing capacity and settlement of a single pile based on the matrix displacement method, which was based on the load transfer function proposed by Heydinger and O'Neill. The method was compared with the classical elastic theory solution and measured data, and the final results showed good consistency between the two.

At present, the research on establishing the pile-soil interaction model by finite element method is not deep enough, and how to reasonably set up the pile-soil interface is still an unsolved problem. In addition, by establishing a three-dimensional model of pile-soil interaction, the influence of different pile diameter, pile length, pile spacing, arrangement, effective pile-soil contact surface and other factors on pile-soil interaction can be analyzed, so as to predict the working condition of filling pile in expansive soil foundation under different working conditions.

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5. Conclusion

At present, experts and scholars have done a lot of research on the engineering properties of expansive soil and the bearing capacity of cast-in-place piles, and have obtained rich research results. However, there are still some deficiencies that need to be improved. The understanding of the swelling and shrinkage mechanism of expansive soil remains to be improved, and the deformation and failure problems of expansive soil foundation are still severe. It is of practical significance to study the relationship between the water content of expansive soil and the parameters of constitutive model, and to modify and improve the constitutive model of expansive soil.

The results of model test can only be a regular discussion, and can not be extrapolated to the actual prototype. It is also necessary to analyze the settlement and horizontal deformation of pile foundation according to the test data of load test, calculate the ultimate bearing capacity and settlement deformation, and compare with the theoretical value to explore the transmission characteristics and deformation laws of regional vertical and horizontal loads, as well as the influencing factors.

In addition, the establishment of three-dimensional finite element model of pile-soil interaction based on appropriate constitutive model is of great significance to engineering practice. By establishing a three-dimensional model of pile-soil interaction, the working conditions of pile-soil interaction under different working conditions can be predicted while exploring the influencing factors of pile-soil interaction.

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