Element, Empirical Rheological Model of Soft Soil

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Abstract. Referring to the relevant articles on the rheological model of soft soil, it is learned that the main research on the rheology of soft soil is focused on the nonlinear creep of soft soil in coastal areas, and various rheological models are used for calculation. The component rheological model and empirical rheological model are selected from the four rheological models. The simple principle, advantages and disadvantages of the model are introduced, and several corresponding studies are listed for further introduction and mainly makes the simplest summary of these studies.

Keywords: soft soil; element rheology model; empirical rheological model; nonlinear.

1 Introduction

Rheology refers to the deformation properties of an object under applied force that are related to practice. In engineering practice, rheological phenomena of soil and rock include creep, relaxation, flow, strain rate effect and long-term strength effect. There are many problems in geotechnical engineering that change with practice. In order to ensure the long-term safety of geotechnical engineering, rheological research of soil and rock is increasingly emphasized [1].

The rheological properties of soil mainly focus on soft soil. Soft soil has a wide distribution range, especially in coastal cities. With the rapid development and land development of coastal cities in China, soft soil has high social value and has become a hot spot for research on engineering properties. Based on the rheological phenomena under one-dimensional vertical compression conditions, there are many studies on phenomena such as secondary consolidation and compression creep [1-3].

Research on rheological properties can be divided into two aspects: micro and macro. The former focuses on starting from the microscopic structure of soil and rock, studying the reasons why soil and rock have rheological properties and the factors that affect the rheological characteristics of soil and rock, but can only conduct qualitative analysis. The latter assumes that soil and rock are homogeneous bodies, and uses intuitive physical rheological models to simulate soil structure. By conducting math-

P. Xiang et al. (eds.), *Proceedings of the 2023 5th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2023)*, Atlantis Highlights in Engineering 26,
https://doi.org/10.2991/978-94-6463-398-6_53

ematical and mechanical analysis on the model and establishing relevant formulas, it quantitatively studies the rheological properties of soil and rock and their impact on engineering.

Rheology, as an important characteristic of soft soil, has always been the focus of geotechnical research and practical engineering. For the foundation composed of a large amount of soft soil, such as land formation and sponge city, this characteristic of soft soil has a significant impact on the structural stability and safety of the upper buildings, which can easily cause a series of serious engineering problems, such as ground settlement and cracking, loss of fill height, secondary geological disasters, and thus cause huge economic losses. Therefore, to study the rheological consolidation characteristics of soft soil, to find the stress-strain and time relationship of soft soil body, and to analyse the essential mechanism of its rheology has become an urgent problem in the field of soil research and practical engineering[4].

After decades of research, the geotechnical engineering community has accumulated a wealth of rheological model data. By classifying and comparing existing models and understanding the characteristics and applicability of each type of model, better research work can be carried out. Yuan [1] classified numerous rheological models into constitutive models, yield surface models, internal time theory and empirical models through comparative analysis. This article focuses on discussing the constitutive rheological model.

2 Introduction to Rheological Model

2.1 Element rheological model

Due to its simplicity, intuitiveness, and clear establishment of constitutive relationships, element models are favored by many scholars for studying soil. Element models use basic model elements such as Hooke's elastic body, Newtonian viscous body, and Saint Venant plastic body to describe certain mechanical properties of soil. For example, springs can be used to simulate the elasticity of soil, and by combining basic model elements, the rheological behavior of soil can be simulated [5]. Data from laboratory tests on the elastic and elastoplastic stages are used to establish models composed of various components to simulate the stress-strain relationship of actual soil. By adjusting the parameters and number of elements in the model, the stress-strain curve of the model can be made to match experimental results.

The Geuze-Chen model marked the beginning of systematic rheological studies of soil. However, natural soil often exhibits nonlinear characteristics, so nonlinear theories were developed, using nonlinear elastic components instead of elastic components [1]. After decades of development, many types of element models have emerged, including three-element models (such as Maxwell and Bingham bodies), Murakami rheological models, modified Komamura-Huang models, Kelvin bodies, and ideal viscoplastic bodies. In theoretical model research, since Dafalias proposed the concept of boundary interface elastoplastic-viscoplasticity in 1982, scholars such as Mosleh A. Al-Shamrani, Stein Sture, and Borja have respectively proposed elastoviscoplastic time-dependent theoretical models [6-7].

2.2 Rheological model of yield surface

Yield surface rheological models study the three elements of elastoplastic theory: yield surface, correlation criteria, and how hardening laws change with time. This type of model combines the study of rheological mechanisms [1].

2.3 Endochronic theory

Since Valanis[8] first proposed the concept of endochronic theory in 1971, this theory has evolved into an effective tool for solving complex elastoplastic problems and has been widely applied in the field of mechanics. The initial concept of the theory is that the current stress state at any point within a plastic or viscoplastic material is a functional of the entire deformation and temperature history in the vicinity of that point. The deformation history is measured using an intrinsic time, which depends on the material properties and the magnitude of the deformation. By studying the irreversible changes in the internal structure of the material represented by internal variables, the evolution laws of these variables can be deduced, and explicit constitutive equations can be derived [1]. However, the endochronic theory is primarily applied in the study of cyclic loading and vibration, especially in the investigation of liquefaction and dynamic constitutive behavior of sandy soils. For instance, Sun [9] conducted research on the non-elastic behavior of sandstone. The application of endochronic theory to relatively static rheological phenomena is relatively limited.

2.4 Empirical model

Empirical models use empirical theory to abstract the stress-strain-time relationship of soil based on experimental results. The most classic empirical creep model is the Singh-Mitchell model, which assumes that the strain of soil is a function of stress and time, and can be expressed as the product of stress function and time function:

$$\varepsilon = f(\sigma, t) = f_1(\sigma)(t) \tag{1}$$

Different empirical formulas can be obtained for different soils and testing conditions [10]. For example, Lu [11] conducted a systematic triaxial consolidation undrained creep test on soft soil in the Zhu Cheng Highway embankment in Hunan. They obtained a stress-strain relationship using a power function and a creep equation with a hyperbolic relationship between strain and time. Zhang [12] performed triaxial drained and undrained creep tests on saturated soft soil in the Zhangzhou area and obtained an empirical creep equation with stress-strain isochronous curves represented by a hyperbolic function and strain-time relationship described by a power function. Lei and Jia [13] proposed an exponential function-based creep model based on the morphological characteristics of creep curves to simulate the nonlinear plastic creep behavior of soft coastal soil in Tianjin. These empirical formulas are derived from specific experimental results and are used to describe the stress-strain and strain-time relationships of soils under specific conditions.

3 Element Rheological Model

3.1 Advantages and disadvantages of element rheological model

The concept of the constitutive model offers intuitive understanding, relatively clear physical significance, and simple calculations [5,11]. However, due to the fact that the constitutive model is composed of linear combinations of model elements, it has a single mechanical property. Sometimes, even by adjusting parameters, it is not possible to accurately quantitatively simulate the measured stress-strain-time curve. Therefore, some scholars choose to connect multiple identical models in series or in parallel to construct more complex generalized models.

However, in nature, soils and rocks often exhibit nonlinear characteristics, leading to the development of nonlinear theories that utilize nonlinear elastic elements to replace elastic elements. However, these models have more complex formulas, and their application in engineering practice is currently limited. Additionally, various factors such as regional differences and sedimentation reasons result in significant differences in the creep characteristics of soft soils in different areas. Therefore, a constitutive model established for a specific region may not be fully applicable to other regions.

3.2 Example of element rheological model

In 1996, Zheng et al. [14] mentioned that most of the model theories used to study rheological problems at that time did not reflect the nonlinear behavior of soils and rocks. They supplemented and modified the existing theoretical models, which could only describe linear rheological processes, with the results of laboratory geotechnical tests. They represented the rheological equation for nonlinear viscoelastic problems as follows:

$$\varepsilon_{ve} = J_{l,ve(t)}\sigma + J_{n,ve(t,\sigma)}\sigma + J_{ve(t,\sigma)}\sigma \tag{2}$$

after entering the plastic rheological stage, the rheological equation is expressed as:

$$\varepsilon_{vp} = J_{l,vp(t)} \cdot (\sigma - \sigma_s) + J_{n,vp(t,\sigma-\sigma_s)} \cdot (\sigma - \sigma_s) + J_{vp(t,\sigma-\sigma_s)} \cdot (\sigma - \sigma_s) \tag{3}$$

Among them, ε_{ve} represents the total strain caused by viscoelastic effects, ε_{vp} represents the total strain caused by viscoplastic effects, σ represents the current stress, and σ_s represents the yield limit strength. $J_{ve(t,\sigma)}\sigma$ represents the total creep compliance for viscoelastic problems, and $J_{vp(t,\sigma-\sigma_s)} \cdot (\sigma - \sigma_s)$ represents the total creep compliance for viscoplastic problems. l and n represent linear and nonlinear components, respectively. By combining equations (2) and (3), the rheological equation for the viscoelastic-plastic model is obtained by expanding and classifying the additive linear and nonlinear components. For three common soft soils in engineering practice in Shanghai, he represented the computational model as Figure 1, Figure 2 and Figure 3:

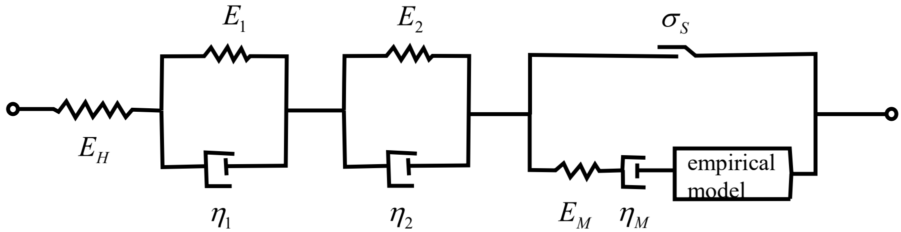

Fig. 1. Viscoelastic-plastic rheological constitutive model of silty clay soil.

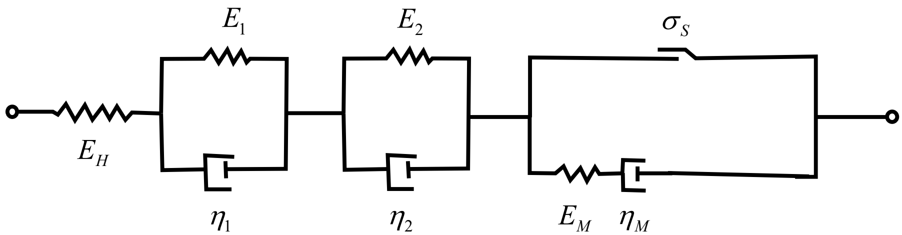

Fig. 2. Visco-elastic-plastic rheological constitutive model of brownish-yellow subclay.

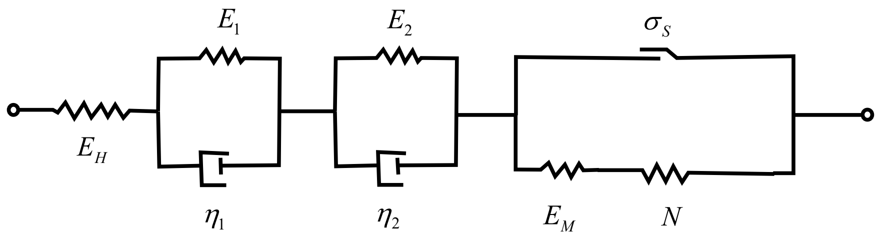

Fig. 3. Viscoelastic-plastic rheological model of dark green subclay.

The principal constitutive relations are respectively:

$$\begin{aligned}\varepsilon_v &= \varepsilon_{ve} + \varepsilon_{vp} \\ &= \varepsilon_{l,ve} + (\varepsilon_{l,vp} + \varepsilon_{n,vp}) \\ &= \left[\frac{1}{E_H} + \frac{1}{E_{K1}} \bullet \left(1 - e^{-\frac{E_{K1}}{\eta_{K1}} \bullet t}\right) + \frac{1}{E_{K2}} \bullet \left(1 - e^{-\frac{E_{K1}}{\eta_{K1}} \bullet t}\right)\right] \bullet \sigma \\ &+ \left\{ \left(\frac{1}{E_M} + \frac{t}{\eta_M}\right) \bullet (\sigma - \sigma_s) + \left[\left(\frac{\sigma - \sigma_s}{A_0}\right)^{m_0} + \left(\frac{\sigma - \sigma_s}{A_t}\right)^{m_0} \bullet t^{\beta}\right]\right\}\end{aligned} \tag{4}$$

$$\varepsilon_v = \left[\frac{1}{E_H} + \frac{1}{E_{K1}} \bullet \left(1 - e^{-\frac{E_{K1}}{\eta_{K1}} \bullet t} \right) + \frac{1}{E_2} \bullet \left(1 - e^{-\frac{E_{K1}}{\eta_{K1}} \bullet t} \right) \right] \bullet \sigma + \left(\frac{1}{E_M} + \frac{t}{\eta_M} \right) \bullet (\sigma - \sigma_s) \quad (5)$$

$$\varepsilon_v = \left[\frac{1}{E_H} + \frac{1}{E_1} \bullet \left(1 - e^{-\frac{E_1}{\eta_1} \bullet t} \right) + \frac{1}{E_2} \bullet \left(1 - e^{-\frac{E_2}{\eta_2} \bullet t} \right) \right] \bullet \sigma + \frac{\sigma - \sigma_s}{E_M} + \left(\frac{\sigma - \sigma_s}{A_0} \right)^{m_0} \quad (6)$$

The three soft soils differ in their nonlinear viscoplastic rheological properties, resulting in differences in the plastic strain portion. Through a comparison of calculated and measured results from engineering examples, there is significant improvement over models without nonlinear elements, with a strong correlation in terms of trends, but there are still some numerical deviations.

After 20 years of research and development, in 2018, Gu et al. [15] further improved the rheological model for soft soils by introducing nonlinear instantaneous elastic modulus. The paper used a series model to simulate layered soil, with different model parameters used to describe its deformation characteristics for each layer. At the same time, a parallel model was used to simulate non-uniform soil, with different model parameters used to describe the deformation characteristics of different parts of the soil. See Figure 4 for details.

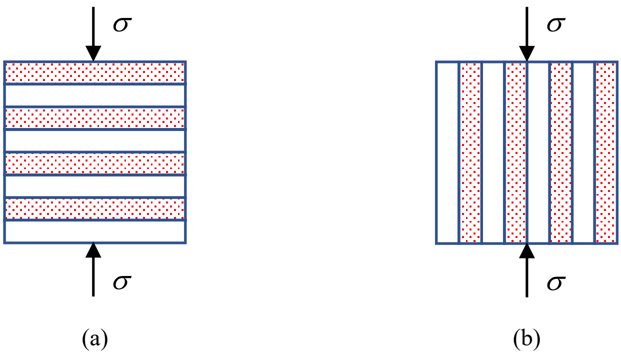

Fig. 4. Modelling of different soil adaptations: **(a)** tandem model. **(b)** parallel model.

Although the accuracy of simulating complex deformation curves improves as the number of model components increases, it also increases the computational difficulty. In this paper, the 7-component model shown in Figure 5 is adopted as the rheological model for soft soil, and two parallel 3-component models ($H_1|N_1|V_1$) and ($H_2|N_2|V_2$) are used to simulate the elastic, plastic and viscous properties of soft soil. In the figure, σ_0 represents the stress; η_1 and η_2 represent the viscosity coefficients of the first and second parallel 3-component models, respectively; E_1 and E_2 represent the Young's moduli of the first and second parallel 3-component models, respectively; V_1 and V_2 represent the stress thresholds of the first and second parallel

3-component models, respectively. The non-linear characteristics of the instantaneous modulus are represented by linear, quadratic and cubic functions based on the results of uniaxial compression creep tests.

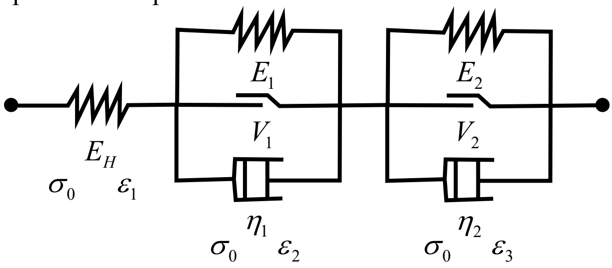

Fig. 5. Seven Component model.

When both $\sigma_0 \le V_1$ and $\sigma_0 \le V_2$, the model becomes a Hoek component with no creep deformation. When either $V_1 < \sigma_0 \le V_2$ or $V_2 < \sigma_0 \le V_1$, the model degenerates into a 4-component model. When $V_1 < \sigma_0$ and $V_2 < \sigma_0$, the model becomes a 7-component model, where the H body, ($H_1|N_1|V_1$) body, and ($H_2|N_2|V_2$) body work together to reflect the viscoelastic-plastic properties of the soil. The solution to the rheological constitutive equation of soft soil is as follows:

$$\varepsilon = \frac{\sigma_0}{E_H} + \frac{\langle \sigma_0 - V_1 \rangle}{E_1}(1 - e^{-\frac{E_1}{\eta_1}t}) + \frac{\langle \sigma_0 - V_2 \rangle}{E_2}(1 - e^{-\frac{E_2}{\eta_2}t}) \tag{7}$$

In the equation, ε represents strain and t represents time. The symbol "< >" denotes that when parameter $A \le 0$, $\langle A \rangle = 0$; and when parameter $A > 0$, $\langle A \rangle = A$. Through analysis and comparison, the results indicate that the 7-component rheological model incorporating the nonlinear characteristics of instantaneous elastic modulus can accurately reflect the rheological properties of soft soil and overcome the issue of model parameters changing with stress levels.

4 Empirical Rheological Model

Empirical rheological models are mostly used in coastal soft ground engineering. In the early stages in China, researchers such as Liu [16,17] proposed an empirical rheological model called space-time theory based on extensive studies of the rheological phenomena of deep foundation pits in the Shanghai. By observing foundation pit construction sites under different construction, geological and support conditions, they performed statistical analysis on more than 100 observed pit deformation data. They derived mathematical equations that correlate the elastic foundation coefficient of passive earth pressure with various construction and soil parameters. The elastic foundation coefficient, k_h, which takes into account the effects of space and time, is a function of several site parameters such as excavation time, space, depth and drawing parameters. It is a semi-empirical parameter based on theoretical principles and is continuously adjusted during construction based on monitoring results to reflect the space-time effect. This approach has opened up a new way of integrating theory and application by taking into account the uncertainties arising from the anisotropy and heterogeneity of geological formations.

In contrast, one of the earliest and most classical empirical creep models abroad, the Singh-Mitchell model, assumes that soil strain is a function of stress and time.

4.1 Advantages and disadvantages of empirical rheological models

Its advantage is that it requires only a small number of parameters to achieve a good fit and it has some practical value in engineering. However, empirical models based solely on indoor experiments lack a rigorous theoretical basis and can only reflect simple creep phenomena under load or sustained force.

4.2 Empirical rheological model cases

In 2006, Zhu et al. [18] applied the Singh-Mitchel creep model with slight modifications to the soft soils in the Pearl River Delta. Based on summarising the results of triaxial creep tests under monotonic loading, the Singh-Mitchel creep model proposed an empirical relationship to describe the stress-strain-time relationship of soil within a stress level range of 20% to 80%. This model uses an exponential function to describe the stress-strain relationship and a power law function to describe the strain-time relationship. The relationship can be expressed as

$$\dot{\varepsilon} = Ae^{a\bar{D}}\left(\frac{t_1}{t}\right)^m \tag{8}$$

upon integration, we obtain:

$$\varepsilon = \varepsilon_0 + \frac{At_1}{1-m}e^{a\bar{D}}\left(\frac{t}{t_1}\right)^{1-m} \tag{9}$$

Assuming $\varepsilon_0 = 0$ to simplify the equation, let $B = \frac{At_1}{1-m}$, $\beta = \alpha$, and $\lambda = 1-m$, we have:

$$\varepsilon = Be^{\beta\bar{D}}\left(\frac{t}{t_1}\right)^{\lambda} \tag{10}$$

In the equation, $\dot{\varepsilon}$ represents the strain rate at any given time, t_1 is the unit reference time, $\bar{D}=\frac{D}{D_{\max}}=\frac{\sigma_1-\sigma_3}{\left(\sigma_1-\sigma_3\right)_f}$ represents the stress level, A is a parameter reflecting the magnitude of the creep rate, α is the slope of the linear segment of the $\ln\varepsilon-\bar{D}$ relationship, and m is the absolute value of the slope of the $\lg\dot{\varepsilon}-\lg t$ relationship. Extensive experimental research, both nationally and internationally, has shown that equation (10) can describe the creep characteristics of various soils and is applicable under different conditions and states.

In 2004, Wang et al. [5] normalised the results of creep tests on soft soils and used a hyperbolic function instead of an exponential function to describe the stress-strain relationship. Mersi et al. also suggested replacing the exponential function with a hyperbolic function. The integral of the Singh-Mitchel empirical formula is expressed as follows:

$$\varepsilon=\varepsilon_0+\frac{At_1}{1-m}e^{aS_1}\left(\frac{t}{t_1}\right)^{1-m} \tag{11}$$

modified to:

$$\varepsilon=\varepsilon_0+C\frac{S}{\sigma-bs}\left(\frac{t}{t_1}\right)^{n} \tag{12}$$

let $C=\frac{At_1}{1-m}a, n=1-m$, modified to:

$$\varepsilon=\varepsilon_0+\frac{At_1}{1-m}\frac{aS}{\sigma-bs}\left(\frac{t}{t_1}\right)^{1-m} \tag{13}$$

In the equation: $\sigma=\frac{\sigma_1+2\sigma_3}{3}$ is the average stress, $S=\sigma_1-\sigma_3$ is the stress variation, t_1 is the reference time, ε_0 is the instantaneous elastic-plastic strain, a and b are the intercept and slope of the straight line in the $\sigma\varepsilon/s$ coordinate, respectively. The parameters C and b reflect the influence of soil material composition, structural properties and stress history on deformation and strength. The parameter n reflects the magnitude of the strain rate and both parameters are determined by values obtained from creep tests on soft soils. Through analysis and comparison, they have a high degree of agreement with the normalised stress-strain relationship curve.

In 2009, Wang [19] studied the creep behaviour of silty clay soft soil in the Tianjin Binhai area through indoor one-dimensional consolidation creep tests. In the study, he constructed a composite model in which the linear part used an element model and the nonlinear part used an empirical model. The specific model structure is shown in Figure 6.

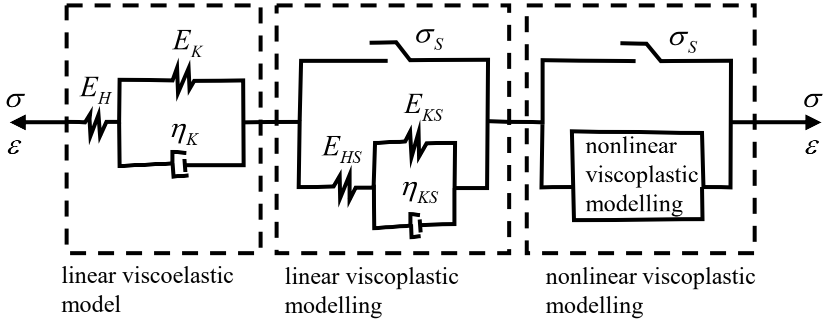

Fig. 6. Rheological model of soft clay.

Non-linear viscoplasticity is represented by an empirical power function formula:

$$\varepsilon_{np} = (\sigma / A(t))^m = (\sigma / A_t t^{-\alpha})^m = (\sigma / A_t)^m t^\beta \tag{14}$$

As the strain is 0 at $t = 0$ and cannot reflect the instantaneous non-linear deformation, an additional term must be added to give the final expression:

$$\varepsilon_{np} = (\sigma / A_0)^{m_0} = (\sigma / A_t)^m t^\beta \tag{15}$$

Where β is the creep index, A_0 and A_t are the non-linear deformation coefficients, m_0 and m are the hardening indices. By taking the partial derivative of equation (15) with respect to time and integrating, the amount of viscoplastic deformation within a given period of time can be obtained. When compared with the measured results from actual engineering, this model shows good agreement with the measured values and can predict the creep trend of the soil.

There have been many studies using empirical models and it is inconvenient to list them all here. Therefore, I have chosen these three representative articles with different improvement approaches for a brief explanation.

5 Discussion

At present, most of the research is only to establish the functional relationship between individual model parameters and the material content of the rheological phase, and the later research can establish the relationship between all the model parameters and the material content of the rheological phase for soft soils with different properties, so that the rheological characteristics of soft soils can be shown by certain parameters, which can make a certain guiding effect on the actual engineering design.

Scholars in the establishment of semi-empirical and semi-theoretical rheological constitutive model, the rheology is divided into linear and non-linear two, due to the huge amount of data and complex processing, the error is very large; so how to further effectively and accurately classify the soft soil rheology, simplify the rheological model still need to be studied.

6 Conclusion

According to the literature on nonlinear rheological models for soft soils, it can be observed that over several decades of development, various calculation models have been proposed by researchers in the field of soil rheology. These models have been continuously modified, improved, and adapted to different regions and types of soft soils in order to enhance their accuracy and applicability. Among these models, constitutive models and empirical models are more mature and widely used, with simpler calculation processes. On the other hand, yield surface models and interior theory have not gained much recognition among scholars and are less convenient for practical engineering applications.

Due to the regional differences in the properties of soft soils, almost all research on rheological models for soft soils focuses on coastal areas. Although significant progress has been made in fitting rheological models to soft soils over the years, the complexity of soft soils and the influence of various factors limit the wide applicability of most models. It cannot be guaranteed that they will still exhibit a high degree of agreement in other regions or under different types of soft soils. Currently, the research on improving the applicability of rheological models is still immature, and the normalization of soft soil rheological calculations remains a challenge. Further research in this area holds significance for future studies.

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