Rheological properties of soil: a review

Guangli Zhu*, Long Zhu and Chao Yu
Transportation Design Co. Ltd. Wuhai Shi-da Inner Mongolia, Wuhai, China

*Corresponding author e-mail: 262427532@qq.com

Abstract. Recently rheological methods have been applied to investigate the mechanical properties of soil micro-structure. Rheological techniques have a number of quantitative physically based measurements and offer a better understanding of how soil micro-structure behaves when subject to stress. Rheological material is refers to deformation properties similar to the solid and flow properties similar to the liquid of bound water and colloidal substances under stress. Soil rheology is divided into fluid rheology and plasticity rheology. Fluid rheology is produced by rheological material. Plasticity rheology mainly refers to the sliding and peristaltic between soil solid particles under shear stress. It is generally believed that the soft soil rheology mainly belongs to fluid rheology, while the rheology of sand and other coarse grained soil mainly belongs to plasticity rheology. Thus, rheology mechanisms of soft soil and sand are different. This paper introduces the methods of the research progress on the rheology of soil, in the soil rheological mechanism, rheological model and rheological numerical aspects of the research at home and abroad were summarized and analysed, discussed the problems existed in related research, and puts forward some suggestions for the future study on the rheology of soil.

1. Introduction
Rheology is the deformation characteristic of the time related to the deformation of the object. The soil has rheological properties, and its common rheological phenomena mainly include creep, relaxation, flow, strain rate effect and long-term strength effect. It is usually used to study the rheological phenomena, to reveal the rheological law and to establish the corresponding theory and calculation method. In recent years, due to the need of engineering construction, the calculation of deformation of soil structure or foundation and strength analysis of the increasingly high demand, must consider the rheology of soil, the soil rheological research becomes one of the hot issues in recent years in the field of geotechnical engineering. The rheological properties of the soil are studied first from the beginning of the experiment, the related research is a lot, its summary or review is also more. On the contrary, the research methods and the constitutive models of the rheological properties of the soil are relatively few, and the analysis of the rheological mechanism is helpful to the understanding and in-depth study of the rheological model. Therefore, this paper mainly analyzes the rheological mechanism of soil, and summarizes the research methods of soil rheology, the rheological model of soil, the solving method and so on.

Because the soil rheology exists, which must be given adequate attention in the design and construction of the geotechnical engineering projects, many projects because of the security risks caused by the rheology of soil also exist in the world. As Japan's first runway of Kansai International
Airport was built in saturated soft soil, started in 1986, completed in 1990, the design of settlement prediction 5.7-7.5m, completion settlement of 8.1m, 1991 to predict the final settlement of 11m, by December 2006, the settlement has reached 12.5m, still continue to produce serious cracks leads to surface subsidence, ground settlement, and maintenance. The cost greatly exceeds the budget, the timeliness of the deformation and foundation of; Shanghai industrial exhibition hall in Shanghai on the soft soil foundation, started in May 1954, completed in June 1957, and on the surface of the central hall of the average settlement has exceeded 160cm, indoor have serious cracks, deformation and rheology of the soil surface. Therefore, the aging deformation characteristics of soil is one of the key research topics in geotechnical engineering.

As early as 1940, Taylor and Merchant took the lead in the consolidation analysis to consider the rheological properties of the soil, the first to have a systematic study of the country is Holland, and the researchers are scholars Geuze. At the time of Holland, some large engineering projects such as the Vlaggeman Bridge, Zuiderzee for seawall rheodestruction, since scientists began to pay close attention to and studied. During the great development of soil rheology can be traced back to 1953, was held in the Third International Conference on soil mechanics and Foundation Engineering Conference (ICSMFE), many scientists of soil rheology problems were reported, since then, the rheology of soil has become a new development direction. Since then, more and more reports about the rheology of soil have become more and more. With the development of science and technology and the continuous increase of the scale of practice, the rheology of soil has been listed as an important scientific research project in many countries such as Holland, Portugal, Japan and so on.

2. Research methods of rheology
The rheological properties of soil can be studied from the view of micro, meso and macro performance. On the micro level, mainly through the intrinsic link between the microscopic characteristics and spatial distribution of contact electron microscope and X ray diffraction instrument of soil particles and aggregates, stacked dimer and micropore micro structure unit connection characteristics and rheological properties of soil. The domestic and foreign scholars have conducted a lot of research work, Chen Zongji put forward the frame structure theory, Shi Bin established a micro mechanical model for simulating viscous soil creep, Mitchell J K, based on the theory of rate processes of the clay stress strain time relation are studied, such as Bazant are used in theory to establish normal transversely isotropic consolidated soil and clay visco elasto plastic constitutive equation. However, due to the complexity and quantitative testing technology of microstructure of clayey soil the limit, plus some physical and chemical properties are difficult to determine, the only micro structure from theory research to make qualitative analysis, it is very difficult to be used in engineering practice.

At the mesoscopic level, the research of soil pore water, types, mineral particles and water adsorption combined with rheological properties of meso structure parameters and soil correspondence and correlation analysis of the quantitative relationship between material factors, rheology of soil physical mechanism, mechanical behavior and rheological properties of the control factors and the parameters, the present study mainly concentrated in the pore water and the bound water, clay mineral types and effects of colloidal substances in the pores on the rheological properties of soil.

In addition, with the rapid development of our country urbanization, the state of infrastructure construction and development of rich marine resources seriously, the coastal towns and port construction land resources are becoming increasingly scarce and precious, at the same time, from a practical sense, the full development of resources and comprehensive utilization, is particularly important to solve and to alleviate Chinese contradiction is much less. In the construction and maintenance of these projects, the cost and environmental pressure mainly include a large amount of silt and dredging soil. Therefore, in order to protect the environment and resources, and maintain the sustainable development of the economy, a lot of silt can be used to engineering construction and maintenance in the process of land reclamation, the benefits of which can alleviate the lack of fill material in coastal areas and can solve a lot of dredging mud way, so it will have a huge environmental and social benefit. Due to the reclamation silt soil and coastal soft soil with soil fine particles, high
water content, high void ratio, low strength, low permeability, consolidation slow, big deformation of engineering properties, so the key techniques of dredger reclamation and coastal soft soil is to overcome the technical problem of the following: how to make the soft soil foundation deformation can be in the water content, consolidation and stability, they can meet the requirement of the superstructure on the bearing capacity of soft soil foundation and long-term settlement.

In the macroscopic aspect, the soil is regarded as a homogeneous continuum, which does not consider the physical foundation of the soil rheology and the factors of the fine structure of the soil. In the rheological model of the structure, irreversible thermodynamics and continuum mechanics are used, and the rheological test results are used to estimate the rheological deformation of the soil. The characteristics of this kind of research are as follows: in the simulation of the macroscopic phenomena of soil mass, the research on this level is more emphasis on the former.

The applicability of rheological measurements as a tool for studying the development of soil structure on the micro-scale is well described in the literature. The fundamental investigations of Mezger, Markgraf et al. and Markgraf and Horn demonstrated the sensitivity of the rheological approach to differ-entiate between the rigidity and the strengthening effects of various substrates. They showed that micro-structural stability is influenced by clay mineralogy and texture, which lead to different shear behavior. Rheological parameters allow a detailed semi-quantitative classification of stiffness degradation, when micromechanical effects on the particle-to-particle scale need to be described. Barré and Hallett investigated the rheological characteristics of wet soils and in particular the effects of soil root, fungal exudates, and clay mineralogy on the stabilization of soil microstructure. They found that analogs of biological exudates increased viscosity by up to 10-fold in some soils dominated by 2:1 clay and at saturated water contents, but the relative effect diminished as soils dried. The stabilizing effect of Biological exudates also decreased with mechan-ical damage.

3. Rheology Mechanism of soil
Is that the rheological mechanism of soil in skeleton stress (effective stress) under the action of soil particles adsorbed on the surface of the water (gas) with viscosity, so that the rearrangement of particles and the skeleton of the dislocation with delay time effect, soil deformation, deformation and time: on the other hand, the soil deformation by boundary this constraint, constraint from the creep deformation trend of development, therefore, the soil stress will gradually adjust, namely the stress change with time. In early 1925, people began to realize that we must establish a true and can reflect the stress-strain relationship of the formula or model clay or other materials fully, according to the micro mechanical deformation on Microstructure on the level of the physical process are described. The concept of physical concepts of clay or other material creep should be belong to the "activation energy".

Bazant and other application rate process theory, a series of constitutive model of soil is established. Shi Bin studied the theory of rate processes in clayey soil creep simulation, introduces the derivation of rate process theory and the corresponding creep model of cohesive soil, the selection of Huaiyin three different types of clay creep test were carried out on, were prepared by the sample structure anisotropic and isotropic, obtained the corresponding results of creep then, the theoretical model of rate process to fit the test results. The results show that the creep process and creep model to trend rate process theory based can effectively simulate different clay and deformation characteristics, reflect the essence of the cohesive soil, soil and soil mechanics closely together. The effects of water, mineral types and organic matter on the rheological properties of soft clay were studied by Gu Renguo and the real light. The direct shear creep apparatus carried out a series of tests on a group of modified clay samples, the test results show that the organic matter and mineral composition and its content is an important factor affecting the rheological properties of soft clay, the viscous coefficient of soil decreases with increasing the content of clay minerals, which decreases with the increase of deformation resistance of organic matter and clay the mineral content, and the influence of organic matter on the rheological properties of soft soil is more obvious. It is concluded that the clay mineral water by combining the rheological properties of soil particles, the strong bound water is the main
factor affecting creep of soft soil, and the weakly bound water is a relatively minor factor. The experimental results can help to further understand the cause of soil rheology, and it is helpful to improve and perfect the existing calculation theory of rheological deformation.

4. Rheological model of soil

Soil rheological model is the soil in the process of mechanical stress and strain - the mathematical description of the time. Just as the soil constitutive relationship plays important role in soil mechanics, rheological constitutive relation of soil is the key to study the rheological properties of soil. In long-term research, people have put forward many kinds of rheological constitutive model of geotechnical material is suitable for analysis of existing models, the rheological model of induction for component model, the yield surface model, damage the rheological model and empirical model.

In engineering practice, the rheological phenomenon of rock soil including creep, stress relaxation and long-term strength reduction, in geotechnical engineering, time must be taken into consideration, in order to ensure the long-term safety of engineering facilities, rheology of rock and soil has been paid more and more attention. On the whole, the study of rheological phenomena is divided into two aspects: microscopic and macroscopic. The former is from the micro structure of rock and soil of rock and soil has rheological properties mainly study the causes and effects of the rheological properties of rock and soil, can only make qualitative analysis on the rheology of rock and soil; the latter assumption of rock and soil heterogeneity, using physical and mechanical means more intuitive to simulate the structure of rock and soil, through the establishment of mathematical model the related formulas are derived, on the rheological properties of rock and soil and its influence on the practical engineering of qualitative research. After decades of development, the geotechnical engineering community has accumulated a large number of data of rheological model, through the comparative analysis found that the rheological model of many can be roughly divided into the following four categories: component model, yield surface model, endochronic model and empirical model.

Element model by Newton N, Hooke dashpot spring H and S nansu SWAI and other basic components reflect the properties of the material, to describe the rheological properties of rock and soil through these basic elements of "series" and "parallel", the establishment of geotechnical constitutive model should reflect the relationship of stress strain time. In component model of two elements model famous Bing ham model, Maxwell model and Kelvin model; multi element model is the mother of the mountain village correction model, tension model, Huang Xiyuan model, Burges model, generalized Maxwell model and generalized Kelvin model, in the village of Liu Bao model, and model and Ma Ming Chen Sofield model. In order to reflect the characteristics of three-dimensional geotechnical materials displayed, based on linear rheological model, according to the principle proposed by Perzyna, using the method of analogy, the one-dimensional soil rheology analysis is extended to 3D, and the model belongs to linear rheological model.

The yield surface rheological model is a study of the variation law of the three elements of the yield surface, the association rule and the hardening law. Olszak and Perzyna first proposed the flow model, which is based on the theory of elastic-plastic theory, the concept of the yield surface, the position and the flow stress, the viscoplastic strain represents the strain history and time and other factors. The flow surface model is usually a hat type model.

Based on the concept of equivalent time and the flow surface theory, Yin, Graham, Zhu Jun advanced a three-dimensional elastic visco plastic (EVP 3D) model. The model assumes that the soil meets the small strain and strain rate can be divided into elastic strain and plastic strain rate of the two part, the elastic strain rate obtained from the generalized Hooke's law, the plastic by the associated flow rule to determine the rate of strain at the same time, it is assumed that the plastic potential function is equal to the current Q function F, to introduce the concept of equivalent time the equivalent time to control the rate of development of visco plastic deformation. The form of the model is simple, the model parameters are small, and the parameters of each model can be determined by the conventional test.
The damage rheological model is according to the basic theory of damage mechanics, the damage considering the mechanical parameters of soil with time equivalent strain, the damage evolution equation is established, and the damage variable is introduced into the constitutive model to establish the rheological constitutive model. For different material properties, stress state, as well as different research methods, research purposes, scholars put forward a lot of damage to the rheological model of rock and soil materials. According to the different research methods of material damage variable, these models can be divided into macro damage model, micro damage model and statistical damage model.

For the empirical constitutive model of rock and soil rheology, it is generally based on the actual engineering test or the laboratory test data to give the function expression of the rheological equation. The experience constitutive model can be divided into empirical function type function relationship between stress and strain or stress strain relationship experience function rate (i.e. the rate type constitutive relation of the letter). The latter is divided into two models, which appear in the constitutive relation and time implicit (including the strain rate) in the constitutive relation. The empirical constitutive relation of soil mass reflects only the external performance of the rheology, which cannot reflect the internal characteristics and mechanism of the rheology, and the difference of the general nature. But it is more intuitive and can be used directly, so loved by engineering designers.

5. Solution of rheological problem of soil mass

In the study of rheology of soil, considering time factors, problems should be solved between the rheological stress strain times than the general elastoplastic calculation of stress strain relationship is more complex, the rheological method needs to be further improved. The solution of the rheological problem of soil mass includes analytical solution and numerical solution.

The analytical solution is the use of the correspondence principle, using the integral transform technique, the specific approach is to first obtain the elastic solution, then Laplasse transform, which must use the elastic constants of the viscoelastic constitutive relation of viscoelastic constants after Laplasse transform are replaced from obtained viscoelastic Laplasse transformation solution by Laplasse inverse transform of viscoelastic final result. The analytic solution is an exact solution, which is based on the application of algebra, calculus and other mathematical principles. The analytical solution of inverse Laplasse transform only some simple and special function can be found, many problems can get a viscoelastic Laplasse transformation solution, but cannot get another analytic inverse solution, rheological problems are relatively complex, it can really get little analytical solution.

With the rapid development of the electronic computing technology, the numerical solution method of the rheological problem is developed. The application and development of numerical solution of soil rheological problem has brought a vital force to the practical application of Rheological Study of soil mass. The basic methods for numerical solutions of the main sometimes step viscous initial strain method, the viscous strain as the initial strain, calculated in each time step viscous initial strain viscous additional load caused by the balance equation is added to the time step in revising and solving, step by step, finally get the solution to the problem of soil rheology. As for the soil nonlinear rheological problem, is the only numerical solution, is generally used when the step incremental nonlinear iterative method, for each load increment, through continuous iteration, with a series of linear rheology to approximate the nonlinear rheological, the nonlinear rheological problem is simplified to linear rheological problems. The numerical solution of the soil rheological problem is mainly used in the finite element method, finite difference method, boundary element method, discrete element method, infinite element method, manifold element method, and so on. The rapid development of numerical calculation method for geotechnical engineering provides a more adequate design basis for complex geotechnical engineering problems. Numerical simulation technology not only substitute and complement the prototype test, model test play, but also to bridge the gap between laboratory test and practical engineering, showing great advantages in the geotechnical engineering nonlinear. However, rock discontinuity, heterogeneity, anisotropy, initial stress and natural boundary conditions such as used in the calculation of rheological constitutive relationship is difficult to accurately grasp the
physical and mechanical parameters of rock mass determination has become a bottleneck problem solving.

6. Conclusions
The soil itself is a heterogeneous system, its rheological property is a more complex problem, research some characteristics only data fitting intuitive, understanding of its internal characteristics and the mechanism is not clear, need to be further in-depth research, to promote and improve the rheological analysis theory and method of soil. With the innovation and development of the related observation and testing technology, it is possible to study the rheological properties of the soil from the perspective of fine and even micro level. At present, the rheology of the soil is mainly focused on the soft soil, the recent development of the study of the rheological properties of sand, the results are less, the depth is not enough. Reflect the rheological constitutive model is not mature, the retaining wall displacement, the settlement of tunnel construction, the excavation process of horizontal and vertical displacement with time development and change, the slope will failure due to long-term strength decreasing with time, and this kind of engineering problems need to be solved urgently study on the rheological model and the calculation method of reasonable. Therefore, the soil rheological still need to test reveal deep rheological properties, and a comparatively perfect model and establish reasonable and reliable method of calculating and analyzing the three aspects at the same time, research, analysis results can provide accurate calculation of Engineering required.

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