Present situation and problems of soil pressure-sinkage model fitting method

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Abstract. The development history of soil pressure-sinkage relationship is briefly introduced. The soil pressure-sinkage model is classified after the research progress of soil pressure-sinkage characteristics at home and abroad was summarized. Several improved models of soil pressure-sinkage based on bekker formula and other models under different soil conditions, such as paddy field soil, desert sand and so on, were introduced respectively. Analyzing the experimental conditions and the theoretical basis of the existing models of soil pressure-sinkage, it is concluded that the existing pressure-sinkage model of soil is established under the condition of the quasi-static loading, the unidirectional applied load, and the assumption that the bottom plate load is evenly distributed. The difference between the experimental conditions of the existing soil pressure-sinkage models and the interaction of pressure-sinkage characteristics between the track of tracked vehicle and ground is analyzed. Based on the finite element simulation analysis and the in situ test, a new idea which can be referenced is proposed to study the interaction of pressure-sinkage characteristics between the track of tracked vehicle and ground from the aspects of loading rate, plate bottom load distribution and cyclic loading and so on.

1. INTRODUCTION

With the development of vehicle ground mechanics, ground measurement technology has gradually formed a measurement form based on geometric definition of horizontal and vertical stress-strain relations and ground irregularities[1]. In the determination of soil stress-strain relationships, semi-empirical methods are used to determine soil stress-strain relationships due to the complexity of soil boundary conditions. The vertical stress-strain relationship of the soil is a very important content for studying the driving performance of vehicles. After decades of development, the research on the characteristics of soil pressure subsidence has made remarkable progress in theoretical innovation and research methods, but there are still problems to be solved. This paper discusses the characteristics, application scope and existing problems of soil pressure subsidence characteristics theory.

2. BEKKER THEORY AND EXPONENTIAL SOIL PRESSURE SUBSIDENCE THEORY

Under the influence of pressure P, equation (1) penetrating into soil depth z:

\[ p \equiv kz^{0.5} \]  (1)

Which was first proposed by the German scholar Bernstein. Where p is the pressure on the plate, k is the inelastic deformation modulus, and 0.5 is the subsidence index.
In 1929, scientists of the former Soviet Union Goriatchkin [2] and others summarized Bernstein’s theoretical improvement of soil subsidence as formula (2):

\[ p = k z^n \]  

(2)

Where: \( p \) is the pressure on the plate, \( z \) is the amount of subsidence, and \( n \) is the soil deformation index.

Baker, on the basis of obtaining a large amount of experimental data and drawing on the load-sag formula in civil engineering, improved formula (2) to formula (3):

\[ p = \left( \frac{k_c}{b} + k_p \right) z^\phi \]  

(3)

In the formula: \( k_c \) is the cohesive deformation modulus, \( k_p \) is the friction deformation modulus, \( b \) is the smaller side of the flat plate size.

The Baker formula eliminates the sensitivity of the soil deformation index \( n \) to the test plate in (2), and the soil parameters are independent of the plate size. This formula has been widely used in the future development of ground mechanics, but it is not perfect. It only considers the effect of plate size on the relationship of soil pressure subsidence, which is inconsistent with the theory of carrying capacity in soil mechanics[3]. After the fifties of last century, the British scholar Reece[4] devoted himself to the study of vehicle ground mechanics. He took into account soil cohesion and soil density, improved the Bekker formula, and obtained formula (4):

\[ \sigma = \left( c' k_c' + \gamma' \frac{b}{2} k_p' \right) \left( \frac{z}{b} \right)^\phi \]  

(4)

In the formula, \( k_c' \), \( k_p' \) are dimensionless parameters, which are more reasonable than the Bekker formula. However, experiments have found that under the same conditions, using rectangular plates and circular plates with a radius equal to the width of the rectangle, different parameter values are obtained, resulting in parameter values that cannot characterize soil properties. Another scholar believes that[3], Bekker's formula ignores the shear effect of the plate edge on the soil, and it is more reasonable to use the plasticity theory to solve the pressure subsidence relationship.

In recent years, scientific and technical workers engaged in research on ground mechanics of vehicles in China have also conducted a lot of research on the relationship between ground pressure subsidence of vehicles and achieved some results. After studying the pressure characteristics of sandy soils, Zhuang Jide et al. [5] researchers improved the Bekker formula, and after a long period of experimental research, a new model describing the characteristics of desert sand bearing subsidence was obtained. In the study of rice soil stress characteristics, Yao et al.[6] proposed a quadratic polynomial model to fit the pressure characteristics of rice soil. In the study of the pressure-bearing characteristics of deep-sea sediments, Zeng Yihui et al. [7] used water-soil mixtures to simulate seabed sediments and obtained pressure subsidence characteristics of water-soil mixtures.

3. CLASSIFICATION OF SOIL PRESSURE SAG CHARACTERISTICS FITTING METHODS

3.1 Bekker theory optimization model

In the process of studying deep-sediment pressure sedimentation characteristics of deep-sediment sediments, there is a situation where it is difficult to obtain in-situ tests and obtain undisturbed sediments because sediments are deeply buried in water. Central South University Zeng Yihui and Hunan University Wang Jiangying [8] used a mixture of bentonite and water in a certain proportion to simulate deep-sea sediments. Among them, Zeng Yihui et al. of Zhongnan University designed a series of pressure-bearing plates to fit the properties of water-soil mixture under pressure and sags. Based on the Baker formula, using a double logarithmic form, as in Equation 5:
In addition, Cai Yan and Wang Xinming et al. \cite{9} used the double logarithm model of Beck’s formula to study the characteristics of soil depression under pressure on the sandy land of Jiangsu Rudong. It was found that the conventional Baker soil constrained depression model could not achieve good results, and it was not as good as the fitting model of the soil pressure model of the southern paddy field.

In the fitting of the subsidence characteristics of the paddy soils in South China, Yang Qiliang and Jiang Chongxian\cite{10} improved on the basis of the Baker formula, using “Equivalent Product Equivalent” as a characteristic parameter of the plate, to comprehensively reflect the shape and size of the plate to the soil load-Subsidence impact. Yang Qiliang and Jiang Chongxian first thought that the load below the measuring plate was not evenly distributed, and can be expressed as Equation 6:

\[
p = p_m \left(1 - e^{-\frac{R-r}{x_p}}\right) + p_c \frac{R-r}{x_p} e^{-\frac{R-r}{x_p}}
\]  

(6)

In the formula: \(r\) — the distance from the center of the plate, \(p_m\) the reaction force in the center of the plate, \(p_c\) the difference between the maximum reaction force and the central reaction force, and \(x_p\), \(x_c\) the parameter of the soil reaction force distribution.

After the integral operation, the load sagging formula of the measuring plate is obtained, as in Equation 7:

\[
W = AP_m + S(e_{x_p} P_c - x_p P_m)
\]  

(7)

Where: \(A\) - measuring board area, \(S\) - measuring board perimeter

Expression 7 is expressed as the average pressure, then:

\[
p = \frac{W}{A} = p_m + (e_{x_p} P_c - x_p P_m) / E_t
\]  

(8)

Where: \(E_t = \frac{A}{S}\), defined as the plate product equivalent.

The combination of \(p = kz^n\), \(P_c\), \(P_m\) respectively, corresponds to \(k_1\), \(k_2\), because in the same soil, the soil deformation index \(n\) is the same. Finally, a formula for describing the sag characteristics of soil in paddy fields was derived, as shown in Equation 9:

\[
p = \left(k_1 + k_2' E_t\right) z^n
\]  

(9)

In the formula: \(k_1' = k_1\),

\[k_2' = (k_c e^{x_p x_c} - k_c) x_p\]

Based on the bekker formula, the author considers the inhomogeneity of the load distribution under the plate, and uses the shape product equivalent to reflect the influence of the plate shape and area on the pressure subsidence of paddy soil. When using a circular plate and a rectangular plate with a small aspect ratio, a good fitting effect can be obtained. However, when a rectangular plate with a large aspect ratio is used, the fitting effect cannot be satisfied due to a condition that \(R >> x_{c}, x_{p}\) cannot be satisfied. Both types of boards are not very good.

When studying the driving of vehicles in the desert and the characteristics of sand pressure sinking, the original Jilin University of Technology Zhuang Jide and other researchers\cite{5}, engaged in related research work for many years, carried out a systematic study of desert sand pressure subsidence characteristics. Taking the Taklimakan desert sand in Xinjiang as an experimental object, an improved bekker formula with a certain angle of the load direction and the ground is proposed.
First, the bekker formula is fitted, and it is found that as the water content of sand increases, the deformation index $n$ is almost constant and the deformation modulus $k$ is reduced. Taking into account the actual conditions of the vehicle, the tire not only generates a vertical load on the ground, but also has the effect of a horizontal tangential load. Zhuang Jide et al.’s researchers proposed an improved bekker formula for tangential and normal forces that are oblique to the ground:

$$q = k' z^{n'}, \quad Q_a = q A / \cos \alpha$$

In the formula, $k'$, $n'$ are the sand deformation modulus and sand deformation index under the action of inclined load; $Q_a$ is the inclined load acting on the pressure plate; and $\alpha$ is the included angle between the inclined load and the vertical direction.

3.2 Other models beyond the classic bekker pressure subsidence model

In the study of the remodeling of soft clay pressure bearing properties, Yao Yan, Ding Qichen, and Zhou Jun [6] of Nanjing Agricultural University used a small-area flat plate to perform plate subsidence tests on soft clay, and obtained a second-order polynomial model that fits the pressure subsidence relationship.

The surface soil of paddy field is taken as an example to study the characteristics of high water content soil under pressure. Xie Xiaoji and Shao Yaojian [11] proposed a segmented model composed of index segments and linear segments derived from Bingham model by observing the flow law of soil under plate loads and determining the pressure subsidence relationship. The flow pattern of the soil under the pressure plate varies with penetration depth, and there is a critical value $z_0$.

Xie Xiaoying et al. first used plate with two areas for silty loam, silty clay and clay with different water content in different ranges, and carried out plate loading test with penetration rates of 0.8 cm/s, 4.5 cm/s, and 9 cm/s respectively. By observing the flow traces of the soil, the results of the theory of soil mobility such as Prandtl’s theory was gotten. When the penetration depth of the soil flow area is less than the critical value, the relationship between soil pressure subsidence can be fitted by the linear segment pushed by the Bingham model. When the penetration depth is greater than the critical value, the relationship between soil pressure subsidence can be fitted by the Bernstein formula.

A summary of the above-mentioned methods for fitting various soil pressure subsidences was conducted. It was found that except for the second-order polynomial model, all other soil pressure subsidence fitting methods were based on exponential form and various improvements were made. Each model method is fitted to a specific type of soil, so its scope of application is not universal. By analyzing the experimental conditions of each model, it is found that the improved model based on bekker model and other exponential models generally belong to quasi-static loading; and the loading method is generally one-way loading, and the pressure subsidence relationship during unloading is not clear enough. The actual distribution of the load below the plate is relatively complex. In the previous research process, it was assumed that the load below the plate was evenly distributed, and the distribution of the load was oversimplified.

4.CONCLUSION

(1) Difference soil pressure subsidence fitting models is Summarized and classified. The first group is mainly including bekker's formula and improved model based on bekker's formula, and the second group is including polynomial model, segmented model combining linear segment and Bernstein's formula introduced by Bingham model, etc.

(2) The experimental conditions and experimental characteristics of the existing pressure subsidence fitting model were analyzed. It is concluded that the pressure subsidence models under various soil conditions are based on ideal conditions such as quasi-static loading, one-way applied load, and uniform distribution of plate bottom load. The existing soil pressure subsidence model is not universal, and most of the models are only suitable for a specific soil type.
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