Establishment and finite element analysis of soil load-sinkage model

Wenxuan Feng [1], Jisheng Ma [2*], Dalin Wu [1], and Jan HE[1]

[1]Army Engineering University, Shijiazhuang Collage, 050003, China,

[2]Xijing University, Xi'an, 710123, China

E-mail: 18533179519@163.com

Abstract. The research of load-sinkage characteristic between soil and vehicle is focused by many scholars in vehicle terramechanics field all the time. The classical models of load-sinkage characteristic between soil and loading plate were established based on a large amount of in-situ tests, but it's sometimes difficult to conduct the in-situ experiments. So the finite element method was used to analyze the load-sinkage characteristic relationship between soil and loading plate based on the triaxial compression experiment date. The finite element calculation result shows that the simulation load-sinkage curve is very close to the curve fitted by classical model. According to the simulation date, a new model,double-exponential equation, to describe the load-sinkage characteristic of soil was proposed, and the $R^2 \geq 0.99$. The new model was verified by fitting the measured date of wet clay and have a better accuracy compared with other models which is bekker、LSA and Kacigin-Guskeo model.

1. Introduction

Vehicle ground mechanics is a discipline that studies the interaction between the vehicle and the ground. It is essential to optimize the vehicle's driving structure and improve the off-road driving ability of the vehicle. Bekker introduced the mechanical interaction between the vehicle and the ground into vertical vertical stress-strain relationship and horizontal stress-strain relationship in the introduction of the ground-vehicle system [1], where the vertical stress-strain relationship is the vertical pressure and subsidence of the soil. Relationship between. From the start of the German scholar Bernstein to establish the relationship between the depth of ground penetration and the ground pressure, scholars from all over the world have conducted different researches on the relationship between soil pressure subsidence.The Soviet scholar Goriatchkin promoted the Bernstein formula as an exponential form. American scholar Bekker proposed the bekker formula based on the above-mentioned two studies and combined with the laws of subgrade settlement in civil engineering. The bekker formula takes into account soil internal friction parameters, cohesive parameters and load plate width, and is a form of soil pressure subsidence relationship index. The representative formula is widely used [2~4]. After decades of development, scholars from all over the world have also proposed many other forms of soil pressure subsidence models.For example, the power function model of British scientist Reece[5], the hyperbolic tangent model of Russian scientist Kurzkov and the hyperbolic model of Japanese scientists[6-7]. Russian scholar Modest Lyasko summed up the experimental results of other scholars and proposed the LSA model with unrelated parameters and experimental conditions [8].

Chinese scholars have also done a lot of research work on the characteristics of soil pressure subsidence. Zhuang Jide et al. took desert sand in Xinjiang as the research object and proposed a model to describe the characteristics of sand pressure subsidence[9]. Yang Qiliang et al[10] used the shape product equivalent as a parameter to reflect the shape and size characteristics of paddles in the study of paddy field subsidence characteristics, and deduced formulas for paddy soil pressure subsidence. Yao Yan et al used the binomial formula to fit the relationship between indoor remodeling soil pressure subsidence and obtained a high accuracy of fitting, and verified the field measured data [11]. Zhao Jiafeng et al combined with soil bearing limit theory proposed an improved soil loading model and verified it with different soil quality parameters to obtain better fitting accuracy [12].

Summarizing the studies of scholars at home and abroad, scholars from various countries have proposed a variety of soil pressure subsidence fitting models in the study of soil pressure subsidence characteristics. In particular, domestic scholars have proposed various targeted models for different soil types.

The application of the finite element method in the analysis of soil mechanics has become increasingly widespread, especially in the analysis of the interaction between the vehicle and the ground [13-15]. In this paper, the soft ground soil was studied, and a fitting model of soil pressure subsidence was established by finite element analysis. The experimental data of the open literature were used to verify the parameters of soil elastic modulus, Poisson's ratio, cohesion and other parameters. The impact was studied.

2. Finite element modeling and comparative analysis

2.1. Determination of soil constitutive relations and parameters

The stress-strain relationship of soil can be described by the elasto-plastic theory in solid mechanics. The mechanical behavior of soil can be divided into elastic behavior and plastic behavior. The elastic behavior is the stress-strain relationship of the soil in the elastic deformation range, which can be described by the elastic constitutive model. The elastic model mainly contains two parameters, which are the elastic modulus E and Poisson's ratio μ. Common soil elastic constitutive models include linear elastic models, porous media elastic models, and linear viscoelastic models. In this paper, the most widely used isotropic elastic model is used to describe the elastic behavior of soil.

The plastic behavior of soil mainly includes yield, hardening, dilatancy and fluidity, which can be described by the plastic constitutive model. The classical soil plasticity constitutive models mainly include Mohr-Coulomb model, Drucker-Prager model and critical state plasticity model [16]. In this paper, the widely used Mohr-Coulomb model is used to describe the plastic behavior of soil.The shear yield function in the Mohr-Coulomb model is:

$$F = R_{mc} q - p \tan \varphi - c = 0 \qquad (1)$$

Where: φ is the friction angle in the q-p plane, c is the cohesion, and Rmc is the shape parameter of the yield function in the π plane.

In the ABAQUS software, non-associated flow criteria is applied to the Mohr-Coulomb model in order to avoid the presence of sharp angles in the yield plane of the π-plane resulting in a non-unique flow direction. And by specifying the relationship between the cohesion c and the equivalent plastic strain, the hardening law of the soil is controlled.

Soil constitutive parameters can be determined by geotechnical tests. The soil shear strength test is one of the tests for measuring the shear properties of soils and is divided into indoor and field tests. The indoor test includes direct shear test and triaxial shear test. The direct shear test apparatus has simple equipment, convenient operation, and little test soil, and can measure the shear strength parameter cohesion c and internal friction angle φ of the soil. The triaxial compression test is another common indoor soil test. Compared with the direct shear test, in addition to the determination of the shear strength index cohesion c and the internal friction angle φ, the soil elastic modulus E and Poisson μ can also be measured [17].

The above two kinds of soil tests were used to determine the parameters of loose soil on the undulating road surface [18]. Under the condition of water content of 5%, the internal friction angle φ=27.33° and the cohesive force c=6.38 KPa were measured. The soil elastic modulus E=20.2 MPa and Poisson's ratio μ=0.32 were measured by the triaxial compression test. The total density is 1932 Kg/m^3.

2.2. Finite Element Model Establishment

Soil stress subsidence characteristics simulation test is a typical nonlinear finite element analysis. The nonlinear sources mainly include nonlinearity of soil material, geometric nonlinearity and contact non-linearity caused by soil deformation under pressure. When using implicit static analysis, the grid distortion is severe and often leads to calculation failure. ABAQUS software provides a series of methods for solving nonlinear problems. For example, ALE method, unit failure method, CEL method. The ALE method is based on displaying dynamic analysis steps. It can perform real-time grid repartitioning for each incremental step in the calculation process to improve the grid quality, and allow custom adaptive division of the area, which can be adjusted by each incremental step. The number of mesh repartitioning controls the strength of the grid's adaptive repartitioning, thereby improving the grid's adaptive partitioning efficiency. The use of display analysis and grid adaptive repartitioning technology can effectively improve the serious problem of grid distortion in the calculation process [19].

The finite element simulation model takes 3D solid modeling. The load plate is a circular plate with radius R=0.1m. In order to simplify the calculation, the loading plate is rigidly constrained by setting the reference point. Considering the influence of the soil model boundary on the simulation results and the simulation calculation efficiency, the soil adopts a cubic model of 1m×1m×1m. The materials cross-section properties of steel and soil are established, respectively. The material parameters of steel are: density 7800kg/m3, elastic modulus E=207GPa, Poisson's ratio μ=0.3; the soil constitutive model adopts isotropic linear elastic model and Mohr-Coulomb model, the parameters are described in 1.1.
The displacement degrees of freedom of the soil model's four lateral are Constrained, and the bottom surface is fixed completely. The loading plate's reference point of freedom in the horizontal direction of freedom and three degrees of freedom of rotation are constrained also. The eight-node linear hexahedral element is applied to the entire model by setting the reduced integration, hourglass control. The soil mesh topology adopts a method of relatively sparsely dense around the middle. The explicit dynamic analysis step is used. A concentrated force, which is 50KN, is applied to the reference point of the loading plate. The model assembly is shown in Figure 1:

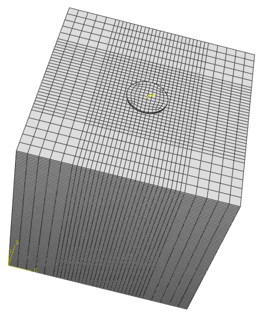


Figure 1. Simulation model assembly

2.3. Comparison of simulation results

Take the vertical displacement load data of the reference point of the loading plate, and use the double exponential equation $F = ae^{(bz)} + ce^{(dz)}$ and $p = kz^n$ to fit the simulation data. The curves are shown in Figure 2:

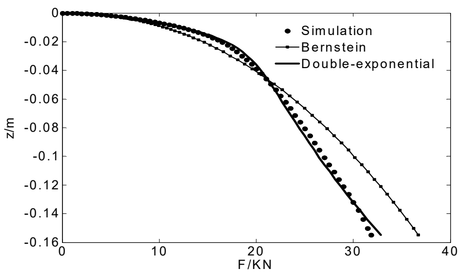
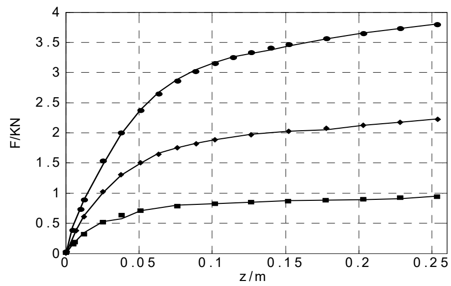


Figure 2. Comparison of double exponential model with classical model

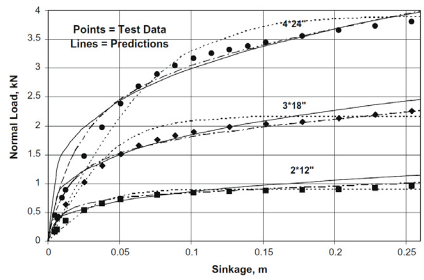
It can be seen from Fig. 2 that the simulation curve of soil pressure subsidence mainly goes through three stages, namely, the elastic deformation stage which the soil is under a small load, and the transition from the elastic deformation to the plastic deformation as the load increases to reach the ultimate bearing capacity. Last is the complete plastic deformation stage. The Bernstein equation has a good fitting effect in the stage of soil elastic deformation,but there is a larger deviation from the fitting curve of the transition phase. The double exponential model has a good fitting effect in different stages of soil deformation. The fitting coefficient R^2=0.9969 is larger than that of the Branstein equation fitting coefficient R^2=0.9821. Use the double exponential model to fit the soil pressure subsidence simulation curve can achieve higher fitting accuracy.

2.4. Double Exponential Model Test Verification

Wills BDM [20] used rectangular plates with dimensions of 2*12, 3*18, and 4*24 inches in wet clay to conduct soil pressure subsidence tests and obtain soil pressure subsidence test data. The Russian scholar Modest Lyasko[8] quoted the results of his experiments using the Bekker model, the LSA model, and the Kacigin-Guskeo function proposed by Kacigin and Guskeo [21-22]. On this basis, a double-exponential model was used to fit the wet clay pressure subsidence test data, and compared with the above-mentioned pressure subsidence model, and the pressure subsidence curve was obtained as shown in Figure 3:



a) Double exponential model fitting curve



b) Bekker, LSD, Kacigin-Guskeo model fitting curve

Note: In Figure (a) ● is 4*24 inch test value, ◆ is 3*18 inch test value, ■ is 2*12 inch test value, in Figure (b)—— For LSA model, ... for bekker model, – – – for Kacigin-Guskeo model

Figure 3. Comparison of double exponential model with experimental data and classical model

As shown in Fig. 3(a), the double-exponential model was used to fit the pressure subsidence data of three sizes of rectangular load plates. According to the size of the loading plate, the coefficient of determination R^2 was 0.9966, 0.9997, and 0.9994, respectively. The verification shows that the double exponential model can fit the measured data of soil pressure subsidence very well. Compared with the results of the fitting of each model in Figure 3(b), the double exponential model has a better fitting effect.

3. Conclusion

Based on triaxial test parameters of soft clay, the finite element model of soil pressure subsidence was established, and the characteristic curve of soil pressure subsidence consistent with the theoretical model was obtained. It is find that the soil pressure subsidence curve established based on the finite element model can be described by $F = ae^{bz} + ce^{dz}$. Fitting the measured data of wet clay pressure subsidence, it is find that it is feasible to use equations $F = ae^{bz} + ce^{dz}$ to predict the relationship of pressure subsidence in wet clay.

References

[1] M G. Bekker. Ground-vehicle system introduction[M]. Beijing: China Machine Press,1978.
[2] LI Jun, ZHANG Yu, ZHOU Jingkai, GONG Cheng-yuan. Study on prediction method of the sinkage of track with big shoes[J]. Agricultural Equipment &Vehicle Engineering,2013, 51(4):33-36.(in chinese)
[3] CAI Wei, WANG Xinming, SUN Jiajun. Measurement of bearing and shearing characteristic parameters of soil in tideland in rudong county of Jiangsu province[J]. Manufacturing Automation,2012,34(3): 133-135. (in chinese)
[4] Lei xueyuan. Optimal design of the track shoe for tracked vehicle[D]. Beijing:Beijing Institute of Technology ,2016.(in chinese)
[5] Reece A R. problems of Soil-Vechicle Mechanics[M]. Michigan: US Army Land Locomotion Lab, 1964.
[6] Zhang Kejian. Vechicle Terramechanics[M]. Beijing: National Defence Industry Press,2002.
[7] LV Weiwei. Research on dynamic coupling characteristics of deformable ground and track plate[D]. Beijing:Beijing Institute of Technology, 2013.
[8] Modest Lyasko. LSA model for sinkage predictions[J]. Journal of Terramechanics, 2010, 47(1): 1-19.
[9] LI Jie, ZHUANG Jide, JI Xuewu. Pressure-sinkage characteristics of desert Sand under a moving vehicle[J]. Acta Armamentarii,1999,20(1): 62-64.(in chinese)
[10] YANG Qiling, JIANG Chongxian. Study on the pressure-sinkage of characteristic in paddy field[J].Transactions of the Chinese Society for Agricultural Machinery, 1990, 9(3): 84-89.(in chinese)
[11] Yao Yan, Ding Qishuo, Zhou Jun. Pressure-sinkage characteristic model of remolded soil[J]. Transactions of the Chinese Society for Agricultural Machinery, 2010,41(3):40-45.(in chinese)
[12] ZhAO Jiafeng,WANG Wei,SUN Zhongxing,SU Xujun.Improvement and verification of pressure-sinkage model in homogeneous soil[J].Transactions of the Chinese Society of Agricultural Engineering, 2016,32(21):60-66. (in chinese)
[13] SHENG Xianfa, ZHOU Hongping, XU Linyun. Nonlinear finite element modeling of track-wheel-ground contact[J]. Mechanical Science and Technology for Aerospace Engineering,2016, 35(2): 315-319.(in chinese)
[14] ZHANG Jinzheng,WANG Qi,JIN Qichun, ZHANG Peng. Simulation research on the dynamic response of the wheel moving load on the ground[J]. Computer Simulation,2016, 33(12): 169-172, 192.(in chinese)
[15] HE Jian, MA Jisheng, WU Dalin, ZHAO Jian-xin. Composite Load-deformation Relationship of

Soil Under vertical and Lateral Loads[J]. Transactions of the Chinese Society for Agricultural Machinery, 2017, 48(9): 231-236.(in chinese)
[16] FEI Kang,PENG Jie.ABAQUS example of geotechnical engineering[M]. Beijing: Posts and Telecom Press,2017.
[17] LI Guangxin. Advanced soil mechanics[M]. Beijing: Tsinghua University Press,2004.
[18] YANG Congbin. Research on the adhesion property of high-speed track on soft ground and optimization of track shoe [D]. Beijing: Beijing Institute of Technology, 2015.
[19] WANG Li,WANG Shimei. Large Deformation Meshing Technology for Soil around the Driven Pile Based on ALE Method[J].Chinese Journal of UndergroundSpace and Engineering,2013, 9(3):530-534.(in chinese)
[20] Wills BDM. The load sinkage equation in theory and practice[J]. LLL report no,1966.
[21] Kacigin VV, Guskoy VV. The basis of tractor Performance theory. Journal of terramechanics,1968,5(3): 43-66.
[22] Guskoy VV. Optimum parameters of agricultural tracters.Moscow: Mashinostroenie; 1966.