Study on Inverse Method of Soil Elastic Modulus Based on Multi-material ALE Fluid-structure Interaction

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Abstract. Because sampling the surface soil appears loose and fracture of soil easily, the elastic modulus of the soil in the tillage layer was difficulty in measuring directly by physical tests. The dynamic simulation model of the cone-air-soil system was established. The multi-material ALE (Arbitrary Lagrangian-Eulerian) fluid-structure interaction method was used in the model. Based on the model, the elastic modulus of the soil was reversed. Meanwhile, the reverse elastic modulus was physically verified by the triaxial test. The results show that the inverse method is feasible. The error is 0.65% compared with the soil elastic modulus obtained by triaxial test. The numerical simulation model of cone-air-soil system has higher precision.

1. Introduction
Soil elastic modulus is not only the important physical and mechanical parameter of soil, but also the basis material parameter of numerical simulation of soil system. The domestic and foreign scholars have studied the elastic modulus of soil material parameter. Yang Guang et al. measured accurately the elastic modulus of clay when they modified side pressure gauge on the soil elastic modulus test and in strict control of the loading speed and rebound times and many other factors[1]. Wang Jianfeng et al. [2] calculated the elastic modulus of clay when applying DCP test method and by measuring the value of cone penetration (DCPI). Mao Xingjun et al. tested the elastic modulus of artificial frozen soil by uniaxial test, and proposed a gray theoretical prediction method for uniaxial elastic modulus of artificial frozen soil[3]. Tian Jia et al. who defined the soil as the ideal elastoplastic material obtained the elastic modulus of soil by triaxial compression test when the soil cohesion and friction angle were obtained by direct shear test[4]. At present, the research mainly focuses on the study of the elastic modulus of soil with deeper soil by physical experiment. However, there are some differences in the nature of the soil at different depths of the tillage layer, and the nature of the surface soil is complicated. At the same time, the soil of the surface layer of the tillage layer is easy to loose and broken, resulting in difficulties in sampling, so that the soil elastic modulus of the soil layer of the tillage layer is difficult to be measured directly by physical test. The method of parameter reversal is an effective method to solve the problem that the physical parameters of materials are difficult to obtain, and there are more applied research[5,6].

In order to avoid the difficulty of sampling in the soil layer of the tillage layer, the indoor remolded soil was chosen as the test object. Firstly, physical experiments were used to determine the basic
physical and mechanical parameters of soil. Then the kinetic numerical simulation model of cone-air-soil system was constructed to reverse the soil elastic modulus.

2. Reverse Method of Soil Elastic Modulus

The TYD-1 soil hardness tester was tested by the WDW3100 microcomputer-controlled electronic universal machine before the soil elastic modulus was reversed, as shown in Figure 1. Because the test machine can show the displacement of the soil hardness tester during the test and the value of the force received. In other words, it can show the penetration depth\( (h) \) of the soil hardness tester and the value of the resistance\( (F) \). Moreover, in the course of the test, the soil hardness meter indicates that the hardness value\( (D) \) can be displayed. Therefore, soil hardness value\( (D) \), soil penetration tester penetration depth\( (h) \) and penetration resistance\( (F) \) will be related. With continuous compression test 20 times, through the regression analysis of the test data, the mathematical model of the depth\( (h) \) and the hardness value\( (D) \) and the cone pressure\( (F) \) of the taper cone inserted into the soil was established respectively[7], as shown in equation (1), equation (2).

\[
D = 2103.9e^{0.14h} 
\]

\[
F = -3.21h + 162.96 
\]

Where, \( D \) is called soil hardness; \( h \) is called soil penetration tester penetration depth; \( F \) is called penetration resistance.

![Compression test of hardness tester](image)

Figure 1. Compression test of hardness tester

The soil hardness\( (D) \) was obtained by using the TYD-1 target soil hardness tester. Based on the measured values and the regression results of the above hardness test, the actual penetration depth\( (h) \) and the penetration resistance\( (F) \) of the hardness tester were obtained. The soil parameters obtained from the physical test include the moisture content\( (\eta) \), density\( (\rho) \), cohesion\( (C) \), internal friction angle\( (\phi) \), and the shear modulus\( (G) \) and bulk modulus\( (K) \) obtained from the initial set modulus of elastic modulus\( (E) \) as the material parameters. Then, based on the multi-material ALE fluid-structure interaction method, the dynamic simulation model of the cone-air-soil system was established. By controlling the single variable and adjusting constantly the initial modulus of elasticity, the elastic modulus is the inverse elastic modulus when the penetration depth and penetration resistance of the cone in the simulation test are close to the actual value and the error is within ± 2%. According to reference [8], the relationship between soil bulk modulus, shear modulus and elastic modulus is shown in equation (3) and (4).

\[
K = \frac{E}{3(1-2\nu)} 
\]
\[ G = \frac{E}{2(1 + v)} \]  

(4)

Where, \( K \) is bulk modulus; \( G \) is shear modulus; \( E \) is elastic modulus; \( v \) is Poisson's ratio. The Poisson's ratio of the soil is generally 0.25-0.37, where \( v \) is 0.3.

3. Measurement of basic parameters of soil

3.1. Determination methods and equipment

In order to compare the elastic modulus obtained by the reverse method and the triaxial test respectively and to avoid the sampling difficulty of the soil in the tillage layer, the remodeled soil was selected and a total of 6 soils were tested. According to the physical test method in the geotechnical test procedure[9], the basic parameters of 6 soils were measured, including hardness(\( D \)), water content(\( n \)), density(\( \rho \)), cohesion(\( C \)) and internal friction angle(\( \phi \)). The equipment used for the determination of these parameters are electrothermal thermostatic blast oven, electronic scale, aluminum box, standard ring knife (volume \( V = 60 \text{cm}^3 \)), strain controlled direct shear apparatus and sclerometer.

3.2. Determination results

Through the measurement and analysis, the hardness(\( D \)), water content(\( n \)), density(\( \rho \)), cohesion(\( C \)) and internal friction angle(\( \phi \)) of 6 soils were obtained, and the average value was obtained, as shown in Table 1.

| Soil material parameter | Soil hardness (N·cm\(^{-2}\)) | Water content (%) | Density (g·cm\(^{-3}\)) | Cohesion (KPa) | Internal friction angle (°) |
|------------------------|-------------------------------|------------------|--------------------------|---------------|-----------------------------|
| mean                   | 26                            | 25.57            | 1.9473                   | 13.843        | 3.434                       |

The soil hardness(\( D \)) is substituted into the equation (1) and (2), and the actual penetration depth (\( h \)) and penetration resistance(\( F \)) of the soil hardness tester are obtained, as shown in Table 2.

| Table 2. Results of soil hardness conversion |
|---------------------------------------------|
| Soil hardness (N·cm\(^{-2}\)) | Actual penetration depth (mm) | Actual penetration resistance (N) |
|---------------------------------------------|
| 26                                           | 31.38                         | 62.23                            |

4. Simulation model of cone-air-soil system dynamics

That the multi-material ALE (Arbitrary Lagrangian-Eulerian) fluid-structure interaction method is selected in the establishment of cone-air-soil system dynamics simulation model because the real soil is prone to large deformation.

The ALE method encompasses the advantages of the Lagrangian method and the Euler method. It not only utilizes the Lagrangian method to effectively track the movement of the boundary of the material structure, but also uses the Euler method to separate the internal grid from the material, so that the grid in the ALE method can be adjusted as needed during the calculation to avoid the serious distortion of the grid.

The simulation steps are as follows: First, a rectangular model is established. The model needs to be divided into two parts. The upper part is the air layer and the lower part is the soil layer. Second, a cone-head model was established above the model to construct a simulation model of ALE fluid-structure interaction for cone-air-soil system. Third, since the entire system simulation model is symmetric, so a quarter of the model has been established in order to reduce the amount of computation. Besides, the grid has been built on the model. Then, add necessary constraint at the
bottom of the soil and the symmetry of the soil. Finally, applying a downward velocity with the actual value on the cone head to simulate the process of inserting the cone into the soil.

Therefore, the geometric dimensions of the selected model should be based on the above requirements and the actual situation. Among them, the cone bottom radius is 0.01m, its height is 0.05m. The size of the soil model is 0.08m × 0.1m × 0.08m, where the air layer thickness is 0.002 m. At the time of modeling, the unit type of the cone is Thin Shell 163 housing finite element, density is 7830kg/m³, elastic modulus is 2×10¹¹ Pa, Poisson's ratio is 0.3 [7]. The element type of soil and air layer is Solid 164 solid finite element element. Since the solid model is spatially symmetric, the solid model is separated by 1/4, and the boundary is treated according to reference [10]. There is a point contact between the cone and the soil. The static friction factor is 0.7, the dynamic friction factor is 0.6, and the cone insertion speed is 0.03m/s [11]. The cone-air-soil system ALE fluid-structure interaction model is shown in Figure 2. The cone-air-soil system ALE fluid-structure interaction simulation model was meshed, as shown in Figure 3. Boundary conditions of the model are also shown in Figure 4. The soil-penetrometer interaction is shown in Figure 5.

![Figure 2. Dynamics simulation model of cone-air-soil system](image1)

![Figure 3. Finite element mesh of 1/4 cone-air-soil model](image2)

![Figure 4. Soil boundary conditions](image3)

![Figure 5. The soil-penetrometer interaction](image4)

5. The results and analysis of the reverse
In the cone-air-soil system dynamics simulation model, the same penetration rate is 0.03 m/s as the actual test, and the same depth is 31.38 mm as the actual test. The penetration resistance of the cone with the penetration time changes in the curve can be get when the elastic modulus $E=0.46$MPa after controlling the elastic modulus of a single variable and several tests, as shown in Figure 6. As can be seen from Figure 6, the penetration depth is 31.38 mm when the penetration time $t=1.044s$, which is the same as the actual penetration depth. And the penetration resistance of the cone is $F_{1/4}=15.8N$, as
shown in point (1.04, -15.8). In the simulation test, the penetration of the entire cone received resistance $F' = 63.2N$ because the simulation model was selected for a quarter of the model before. At the same time, the actual resistance of the penetration resistance $F$ is 62.23N, the error within $\pm 2\%$, so at this time, the elastic modulus in the simulation model is the reverse elastic modulus.

The soil elastic modulus($E$), the corresponding bulk modulus($K$) and shear modulus($G$) obtained by the inverse method are shown in Table 3.

| Elastic modulus (Mpa) | Bulk modulus (Mpa) | Shear modulus (Mpa) | relative error between $F'$ and $F$ (%) |
|-----------------------|-------------------|--------------------|-----------------------------------|
| 0.46                  | 0.3833            | 0.1769             | 1.5                               |

6. Verification and Analysis of Soil Elastic Modulus

In this paper, the soil elastic modulus of the above method is verified by indoor triaxial test. The triaxial test is a shear test method for determining the shear strength parameters of the soil under three-way pressure conditions. With reference to the soil of the triaxial test method in the geotechnical test procedure [9], the rubber film will be smoothly wrapped in the soil sample into the pressure chamber. Under the confining pressure of 50 MPa, the axial pressure was applied to shear the cylindrical soil samples until the soil samples were destroyed. Then, according to the relationship between soil stress and strain, the elastic modulus of soil samples is obtained.

According to the mechanics of materials, the relationship between soil stress and strain is shown in equation (5). Therefore, the elastic modulus of soil is obtained because the relationship between soil stress and strain is shown in Figure 7. The elastic modulus of soil $E$ is 0.457MPa.

$$E = \frac{\Delta \sigma}{\Delta \varepsilon}$$  (5)

Where, $E$ is elastic modulus of soil; $\Delta \sigma$ is soil stress; $\Delta \varepsilon$ is soil strain.

![Figure 6. Relationship between penetration resistance and penetration time](image1)

![Figure 7. Stress strain relationship of soil sample](image2)

The error of elastic modulus of the soil obtained by the triaxial test is 0.65% (within $\pm 2\%$) compared with the elastic modulus obtained by the inverse method. It is proved that the soil elastic modulus obtained by the inverse method is correct and feasible.

7. Summary

The dynamic simulation model of the cone-air-soil system was established. The multi-material ALE (Arbitrary Lagrangian-Eulerian) fluid-structure interaction method was used in the model. Based on
the model, the elastic modulus of the soil was reversed. Meanwhile, the reverse elastic modulus was physically verified by the triaxial test. The results show that the inverse method is feasible. The error is 0.65% compared with the soil elastic modulus obtained by triaxial test. The numerical simulation model of cone-air-soil system has higher precision.

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References
[1] Yang G. and Tian K.L. (2006). Study of Soil Elastic Modular Test Method. Urban Roads Bridges & Flood Control, vol 5, pp. 145-147+208.
[2] Wang J.F., Wang Z., and Deng W.D.(2007). Simple Method to Evaluate Resilient Modulus of Subgrade Cohesive Soils. Journal of Wuhan University of Technology(Transportation Science & Engineering), vol 5, pp. 800-803.
[3] Mao X.J.(2014). Grey prediction of uniaxial elastic modulus of artificial frozen soil. Sichuan Building Materials, vol 3, pp. 95-97.
[4] Tian J., Cao B. and Ji J.N. (2015). Numerical simulation and validation test of direct shear test for root-soil composite of Hedysarum scoparium using finite element method. Transactions of the Chinese Society of Agricultural Engineering, vol 16, pp. 152-158.
[5] Cooreman S, Lecompte D and Sol H, et al(2007). Elasto-plastic material parameter identification by inverse methods: Calculation of the sensitivity matrix. International Journal of Solids and Structures, vol 44, pp. 4329-4341.
[6] Molimard J, Riche R L and Vautrin A, et al(2005). Identification of the four orthotropic plate stiffnesses using a single open-hole tensile test. Experimental Mechanics, vol 45, pp. 404-411.
[7] Yang W., Zhang S. and Chen K.Y.(2016). Dynamics Simulation Model of Cassava Tuber Lifting System Based on Soil Layering. Research on Agricultural Mechanization, vol 8, pp. 51-55.
[8] Zhang S. Study on dynamic simulation model of cassava root pulling system based on soil layer, Nanning: Guangxi University, 2014.
[9] Ministry of water resources and electric power of People's Republic of China, Geotechnical test code SD128-84 First fascicle. Beijing:Water conservancy and electric power press,1987.(Book)
[10] Yang Wang,Li Juanjuan and Yang Jian, et al(2015). Numerical simulation of an experienced farmer lifting tubers of cassava for designing a bionic harvester. CMES: Computer Modeling in Engineering Sciences, vol 104, pp. 471-491.
[11] Li Y.J.,Lin J.H. and Xu Y.(2011). Simulation of penetration test of cone index instrument by discrete element method. Journal of agricultural machinery, vol 11, pp. 44-48.