

Research Article

An Improved Nonlinear Settlement Calculation Method for Soft Clay considering Structural Characteristics

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The settlement calculation model for soft clay foundation is established based on Hooke's law and the Duncan-Chang model. By introducing the concept of damage ratio, the method for determining the deformation modulus of soil before and after damage under load is presented, and a nonlinear settlement calculation method which considers the structural characteristics of soft clay is proposed. In the end, a practical engineering example is analyzed with the proposed method and some current methods for soft clay settlement calculation. The results indicated that the proposed method is feasible and applicable in practical engineering.

1. Introduction

The structure of soil is defined as the manner of arrangement and state of aggregation of soil grains. Most natural soft clays have a certain structure [1, 2] and are influenced by factors such as precipitation, unloading, and weathering. A large number of practical engineering projects have proven that structure is an important feature of soft clay and an important factor that affects the final settlement and settlement rate of soft clay [3]. Therefore, it is of significance to investigate the settlement calculation method of soft clay and establish a new calculation method of settlement of soft clay considering the structure of soil.

For the past decades, many settlement calculation methods for soft clay have been conducted by scholars. Shen [4, 5] introduced the damage theory into the description of the mechanical behavior of structural soils and established the evolution law of soil damage; Zhang [6] established the statistical relationship between laboratory test data and in situ test data based on the practice in the Shanghai-Nanjing Expressway and proposed the settlement calculation method

considering the effect of structural characteristics. Shi et al. [7] used the finite element method to analyze the settlement and deformation of the embankment on the soft foundation considering the rheology and damage of the structural soil based on the double yield faced elastoplastic model proposed by Yin. However, the complexity of the constitutive model made it difficult to obtain certain parameters and difficult to be applied in engineering practice; Wang and Chen [8, 9] made piecewise linearization of the curves of consolidation coefficient C_v and consolidation pressure p and permeability coefficient k and consolidation pressure p by taking yield stress as the piecewise point. Based on this, an analytical expression was obtained to calculate the one-dimensional consolidation degree of the structural soft clay foundation, yet such a two-stage simplification would have a certain impact on the calculating accuracy. Based on the Duncan-Zhang model, considering the structure of soft clay, the concept of damage ratio was introduced to modify the Duncan-Zhang model by Wang et al. [10, 11]. Li et al. [12] analyzed the influence of soft clay structure on its own deformation and deformation rate based on the results of one-

dimensional consolidation and permeation tests of undisturbed soil and remolded soil. Lu [13] applied the structural damage theory to the settlement calculation of soft clay and proposed a revised settlement calculation formula based on the Duncan-Zhang model, considering the influence of Poisson's ratio on the settlement of the foundation with the change of its stress. Feng et al. [14] presented a simplified method for calculating multistage creep settlement of multilayer soft clays under one-dimensional strain conditions. Rui et al. [15] used an analytical method to calculate the compressibility of the pile-soil system; the settlement characteristics of granular filler on saturated soft clay foundation with time were studied. Zhao et al. [16] established a nonlinear elastic-viscoplastic creep constitutive model and verified it by experiments. Yu et al. [17] investigated a time-dependent deformation mechanism in depth and obtained the viscoelastoplastic deformation of soft soil using a non-associated flow rule and the modified Nishihara model. Yu et al. [18] performed the numerical simulations with the use of a two-dimensional discrete element method, in which the numerical model is calibrated to match the stress-strain and permeability-strain responses of the experimental results. Simulation results reveal that the settlement calculation of soft clay considering the structural damage is feasible. However, obviously none of these methods avoids the defect in that the Duncan-Chang model does not consider the volumetric stress.

In summary, how to consider the structure of the soil itself in the settlement calculation is a question which is worthy of consideration. Therefore, this paper starts with the discussion of the deformation mechanism of the soil element and combines Hooke's law and the Duncan-Zhang model to establish a new calculation method for the settlement of the foundation considering the soft clay structure.

2. Analytical Model

In order to reflect the settlement process of weak ground more accurately, this paper introduces the Duncan-Zhang model to describe the stress-strain relationship of soil deformation. The Duncan-Zhang model is based on the Kondner hyperbolic relationship [19], and its expression is

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1}, \quad (1)$$

where σ_1 is the vertical stress of soil, σ_3 is the confining pressure of soil, ε_1 is the vertical strain of soil, and a and b are the triaxial test curve fitting parameters, which can be explicitly calculated by the below formulas:

$$a = \frac{1}{E_0}, \quad (2)$$

$$b = \frac{1}{(\sigma_1 - \sigma_3)_u} = \frac{R_f}{(\sigma_1 - \sigma_3)_f} = \frac{R_f(1 - \sin \varphi)}{2c \cos \varphi + 2\sigma_3 \sin \varphi}, \quad (3)$$

where E_0 is the initial deformation modulus of soil; R_f is the coefficient of soil failure ratio or strength, generally taken as 0.75~1.0; C is the cohesion of soil; and φ is the friction angle of soil.

Apparently, the effect of the soil stress difference ($\sigma_1 - \sigma_3$) on the vertical strain ε_1 when the confining pressure σ_3 is constant is considered in the Duncan-Zhang model [20], while the effect of the volume stress on the soil compression deformation is not taken into account. The Duncan-Zhang model cannot be used directly for settlement calculation of soft ground. Therefore, this paper divides the additional stress into two parts: partial stress ($\sigma_1 - \sigma_3$) and volume stress $(\sigma_1 + \sigma_2 + \sigma_3)/3 = \sigma_3$. Therefore, the deformation of the soft clay foundation under the effect of additional stress should be determined by the deviatoric stress and volumetric stress. The layer-wise summation method is still used to calculate the settlement of soft soil foundation. The total settlement of the soft clay foundation is

$$s = \sum_{i=1}^{N_i} s_i = \sum_{i=1}^{N_i} (s_i' + s_i''), \quad (4)$$

where i is the total compression deformation of the i layer soil, s_i' is the deformation of the i layer of soil under the action of volume stress σ_3 , s_i'' is the deformation of the i layer of soil under the action of deviatoric stress ($\sigma_1 - \sigma_3$), N_i is the number of layers of the ground compression layer, and d_i is the thickness of the i layer of soil. The solution process of deformation s_i' and s_i'' of each compressive layer of soft clay under the effect of additional stress will be described in the following sections.

3. Establishment of Method

In this study, the principle of damage mechanics is introduced into the calculation of foundation settlement and the traditional layered sum method is further modified.

In addition, the gravity stress also causes the initial mechanical parameters due to the different stress history of each soil layer, that is, during deformation of soils. This phenomenon also should be studied.

However, as the physical and mechanical parameters of the soft soil, especially its deformation modulus, will also change during the deformation process, it is difficult to solve it with the traditional control differential equation method. Therefore, based on the idea of step loading, this paper introduces the incremental method which is used to calculate s_i' and s_i'' , and a settlement calculation method for soft clay foundation is proposed.

It can be seen that when the damage principle is combined with the layer-wise summation method to calculate the settlement of the soft clay foundation, the changes in the physical and mechanical parameters of the various soil layers must be considered. Based on the above considerations, a calculation method for the settlement of soft soil foundation as shown in Figure 1 is proposed.

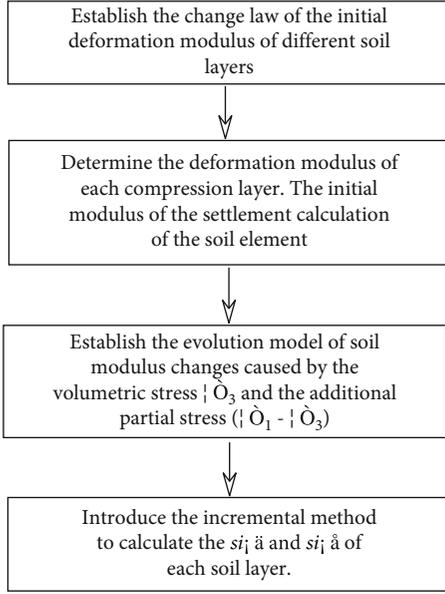


FIGURE 1: Calculation flowchart.

3.1. Damage Variable D . This article introduces the definition of the damage variable D of Shen [4] and treats the failure process of the soil as a process of gradually transforming from the undisturbed soil to the disturbed soil (damaged soil). Constantly changing, its changing law can be expressed by the following formula:

$$E' = E(1 - D), \quad (5)$$

where $D = 1 - e^{-(m\varepsilon_v + n\varepsilon_\beta)}$

$$\begin{aligned} \varepsilon_v &= \varepsilon_1 + 2\varepsilon_3, \\ \varepsilon_\beta &= |\varepsilon_1 - \varepsilon_3|, \end{aligned} \quad (6)$$

where D is the damage variable, ε_v is the volumetric strain, and m and n are the test parameters, obtained from confined and unconfined compression tests. Let e_m be the turning point void ratio when the compression curve of the undisturbed soil and the compression curve of the remolded soil are substantially parallel in the confined compression test. Assuming that D is 0.95, the expression of m can be obtained as

$$m = \frac{\ln 20}{(e_0 - e_m)/(1 + e_0)} - n, \quad (7)$$

where e_0 is the initial porosity of soil.

We suppose that $D = 0.95$ at the turning point ε_n at the later stage of the descending section of the stress-strain curve in the confinement test. Considering $\varepsilon_v = 0$ at this time, the expression of n can be obtained as

$$n = \frac{\ln 20}{1.5\varepsilon_n}. \quad (8)$$

Considering that ε_n is difficult to calculate, the empirical formula of reference [5] is still cited:

$$\varepsilon_n = \frac{e_m}{1 + e_0}. \quad (9)$$

3.2. Initial Deformation Modulus. As a result, the structure of the soft soil itself is affected by the load, and the soil is damaged, which causes the deformation-related mechanical parameters, that is, the deformation modulus, to change continuously. At the same time, different stress history conditions, that is, gravity stress, will cause different degrees of damage to the soil. Therefore, the change law and determination method of the deformation modulus of each soil layer of the foundation should be studied in depth.

Let the horizontal direction be the x -axis and the y -axis, and the vertical direction be the z -axis. Since the soil layers below the centerline of the foundation are mainly subject to gravity stress, in this coordinate system, the stress state of each soil element is the main stress state. The large principal stress is σ_1 , and the small principal stress is $\sigma_2 = \sigma_3$. Then, the expression of the i compression layered gravity stress is

$$\sigma_{1i} = \left(\sum_{t=1}^{i-1} \gamma_t d_t + \frac{\gamma_i d_i}{2} \right), \quad (10)$$

$$\sigma_{3i} = k_0 \sigma_{1i}, \quad (11)$$

where γ_t is the gravity of the t layer soil, d_t is the thickness of the t layer soil, σ_{3i} is the lateral stress of the i soil element, σ_{1i} is the vertical average gravity stress of the i soil element, and k_0 is the lateral pressure coefficient. Under lateral conditions, its expression is

$$k_0 = \frac{\mu}{1 - \mu}, \quad (12)$$

where μ is Poisson's ratio of the soil. Considering the deformation mechanism of the soil element, the gravity stress of the soil element is divided into two parts which are the gravity volumetric stress σ_{3i}^v and the gravity partial stress $\sigma_{(1-3)i}^p$. The expressions are

$$\sigma_{3i}^v = \frac{\sigma_{3i} + \sigma_{3i} + \sigma_{3i}}{3} = \sigma_{3i}, \quad (13)$$

$$\sigma_{(1-3)i}^p = \sigma_{1i} - \sigma_{3i}. \quad (14)$$

The completed compressive deformation caused by the gravity volumetric stress and the gravity partial stress can be calculated by Hooke's law and the Duncan-Zhang model, respectively. At the same time, the idea of step loading is introduced and the effect of the gravity volumetric stress and the gravity partial stress on the soil itself is. During the loading process, the number of loading stages is N . Among them, σ_{3i}^v and $\sigma_{(1-3)i}^p$ represent the stress increment caused by the j gravity volumetric stress and the gravity partial stress of the i soil in the compression layer.

$$\sigma_{3ij}^v = E_{i(j-1)} \varepsilon_{3ij}^v + \mu \left(\sigma_{3ij}^v + \sigma_{3ij}^v \right), \quad (15)$$

where ε_{3ij}^v is the strain under the j gravity volumetric stress and $E_{i(j-1)}$ is the deformation modulus of the i layer soil after the $(j-1)$ level gravity stress, so that

$$\varepsilon_{3ij}^v = \frac{(1-2\mu)\sigma_{3ij}^v}{E_{i(j-1)}}. \quad (16)$$

This article introduces the damage principle proposed by Shen [4]. The change formula of the deformation modulus E_{ij} of the i layer soil at the j gravity volumetric stress is

$$E_{ij} = E_{i(j-1)} \left(1 - D_{ij}^v \right), \quad (17)$$

where

$$D_{ij}^v = 1 - e^{-\left(3m\varepsilon_{3ij}^v \right)}. \quad (18)$$

Since the increment of the j -th gravity partial stress will inevitably cause further damage to the soil, under the action of the corresponding gravity partial stress increment $\sigma_{(1-3)ij}^p$, its deformation modulus E_{ij} will continue to change accordingly, assuming the soil element at this time. The stress-strain relationship obeys the Duncan-Chang model, where E_{ij} is used as the initial tangent modulus of the model, and the tangent modulus of the Duncan-Chang model curve is the deformation modulus of the soil after the increase of the weight and deflection stress when the deflection stress is $\sigma_{(1-3)ij}^p$. Through the above two steps, the deformation modulus of the i layer of soil can be obtained after the j gravity volumetric stress and deviatoric stress. The specific calculation method is as follows:

According to formula (1), the deformation of the soil under the action of the j gravity partial stress increment $\sigma_{(1-3)ij}^p$ is

$$\varepsilon_{(1-3)ij}^p = \frac{a\sigma_{(1-3)ij}^p}{1 - b\sigma_{(1-3)ij}^p}, \quad (19)$$

$$\varepsilon_{3ij}^p = -\mu\varepsilon_{(1-3)ij}^p, \quad (20)$$

where

$$a = \frac{1}{E_{ij}}, \quad (21)$$

$$b = \frac{R_f(1 - \sin \varphi)}{2c \cos \varphi + 2\sigma_{3ij}^p \sin \varphi}. \quad (22)$$

The relationship between the deformation modulus E_{ij} of the i layer of soil before and after the j gravity partial stress increase $\sigma_{(1-3)ij}^p$ is

$$E_{ij} = E_{i(i-1)} \left(1 - D_{ij}^p \right), \quad (23)$$

where

$$D_{ij}^p = 1 - e^{-\left(m(1-2\mu) + n(1+\mu) \right) \varepsilon_{(1-2)ij}^p}. \quad (24)$$

From this, it can be seen that using formulas (17) and (23) to calculate the initial modulus of each soil layer is an iterative process. The specific calculation steps are as follows:

- (1) Give the initial deformation modulus E_{i0} and Poisson's ratio μ at the zero-stress level of the i layer of soil
- (2) From formulas (10) to (14), the first-layer gravity volumetric stress ε_{3i1}^v and the gravity partial stress $\sigma_{(1-3)il}^p$ of the i layer of soil are calculated. Calculate the vertical strain ε_{3i1}^v under the gravity volumetric stress σ_{3i1}^v from equation (16)
- (3) From equations (17) and (18), the change value E_{i1} of the deformation modulus of the i layer soil caused by the gravity volumetric stress σ_{3i1}^v at the first level can be obtained
- (4) Taking the deformation modulus E_{i1} as the initial modulus before the gravity partial stress $\sigma_{(1-3)il}^p$, the vertical strain $\varepsilon_{(1-3)il}^p$ under the gravity partial stress $\sigma_{(1-3)il}^p$ is calculated from equations (19) to (22)
- (5) Calculate the deformation modulus E_{i1} of the i layer soil after acting on the first-level gravity partial stress $\sigma_{(1-3)il}^p$ from equations (23) and (24)
- (6) Return to Step (2); continue to calculate the deformation modulus of the i layer soil under the influence of various levels of loads, until the deformation modulus E_{iN} of the soil after the N layer gravity stress loading is obtained; and calculate it as the additional stress settlement initial modulus

The following will further study the calculation method of foundation settlement analysis.

3.3. Settlement Calculation Steps. This paper believes that the total settlement of the foundation should be divided into the sum of the settlement caused by additional volume stress and the settlement caused by additional deviatoric stress, that is, the sum of the compression layers s_i' and s_i'' in the settlement model established earlier. The consolidation deformation calculation steps have been completed for analysis and calculation.

Meanwhile, Boussinesq's stress solution is introduced to obtain the vertical stress and lateral stress caused by the additional stress in the soil of the i layer. The corresponding additional volume stress and additional deviator stress are σ_{3i} and $(\sigma_{1i} - \sigma_{3i})$, respectively. The deformation of the i layered soil is s_i' and s_i'' . The solution process is as follows:

TABLE 1: Parameters for calculation.

Soil layer	Poisson's ratio, μ	Unit weight, γ (kN·m ⁻³)	Cohesion, C (kPa)	Friction angle, φ (°)	Initial porosity, e_0	Initial deformation modulus, E_0 (MPa)
Zhanjiang clay	0.38	17.3	36	23.5	1.45	3.4

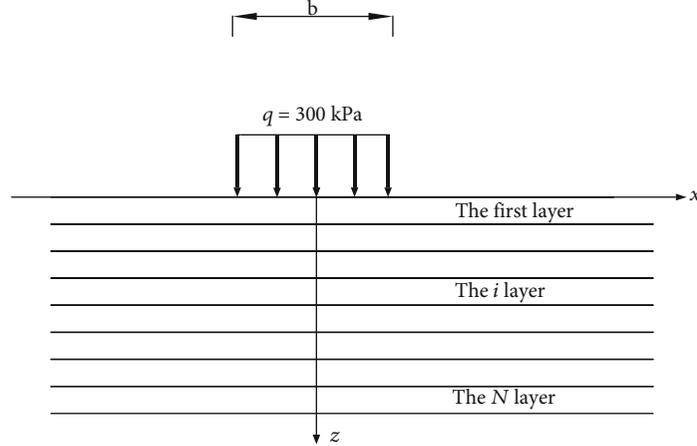


FIGURE 2: Diagram of soil layers under strip foundation.

- (1) The soft clay foundation compressed soil layer is divided into N_i layers, the thickness of each layer is d_i , and the initial deformation modulus E_{i0} and Poisson ratio μ of each compressed layered soil are given
- (2) The final change value of the deformation modulus E_{iN} caused by the soil damage caused by the gravity stress of the compressive layered soil of the soft clay in Section 3.2 was calculated by the method in Section 3.2, and E_{iN} was used as the initial modulus of the settlement calculation of the i layer soil
- (3) Let the number of additional stress loadings be M and the load at each stage be p_i . The additional volume stress σ_{3i1}^v and the additional deviatoric stress $\sigma_{(1-3)il}^p$ of the i layer of foundation soil under the action of the first-stage additional load p_i can be obtained from Boussinesq's solution
- (4) Let E_{i0} denote the initial modulus of the foundation soil of the i layer, that is, $E_{i0} = E_{iN}$, as the strain ε_{3i1}^v and deformation modulus E_{i1} of the foundation soil of the i layer after the action of the first-level load σ_{3i1}^v can be obtained by formulas (16)–(18)
- (5) Taking E_{i1} as the initial modulus before the second-stage loading, the strain $\sigma_{(1-3)il}^p$ and deformation modulus E_{i1} of the i layer soil after the action of the first-stage additional deviatoric stress $\sigma_{(1-3)il}^p$ are obtained by equations (22) to (26)
- (6) Multiplying the strain of each soil layer under the first-level additional stress by the thickness of the

corresponding layer is the total settlement of the soft clay foundation under the first-level additional stress:

$$s_1 = \sum_{i=1}^{N_i} s_{i1}' + s_{i1}'' = \sum_{i=1}^{N_i} (\varepsilon_{3i1}^v + \varepsilon_{(1-3)il}^p) d_i. \quad (25)$$

- (7) According to the above steps, we continue to calculate the strain, deformation modulus, and total settlement of each soil layer of the foundation under the M -level additional stress
- (8) The total settlement is obtained by superimposing the settlement of each soil layer under the M -level additional stress:

$$s = \sum_{j=1}^M s_j. \quad (26)$$

4. Illustrative Example

In order to verify the accuracy and rationality of the method proposed in this paper, the parameters collected in this paper based on the experimental data of Zhanjiang clay [21] are shown in Table 1, and $e_a = 0.81$, $\varepsilon_b = 0.26$, and the surface load is 300 kPa, divided into 6 Add 50 kPa per day for stage loading to calculate the settlement and deformation of the foundation under the strip foundation, as shown in Figure 2.

Using the above data to calculate the settlement using this method, the specific process is as follows:

TABLE 2: Calculating results.

Calculation method	Settlement (cm)	Measured settlement (cm)
Method by Reference [21]	15.0	15.16
This study	17.53	15.16

- (1) When the additional stress σ_{zi} and average gravity stress σ_{czi} of the i layer soil satisfy $\sigma_{zi}/\sigma_{czi} \leq 0.1$, the calculated total thickness of the compression layer can be determined to be 6.4 m, and the layer thickness can be determined according to $d_i \leq 0.4b$ (b as the basic width), which is 0.4 m for each layer (total 16 layers)
- (2) Calculate the gravity stresses σ_{1i}^c and σ_{3i}^c of each soil layer in the compression layer range and divide them into 5 levels of loading, that is, $N = 5$
- (3) Determine the additional stresses σ_{1i}^z and σ_{3i}^z of each compression layer under the upper load of each stage
- (4) According to the calculation method steps of Section 3.2, the total settlement of the foundation soil is 17.53 cm

The calculation results are compared with the results in reference [21], as shown in Table 2.

It can be found in Table 2 that the method in this paper agrees well with the actual measured values of the project. The damage mechanics model considering the damage process of clay structures established in [21] has developed a corresponding finite element program for calculation. Nine parameters need to be determined by confined and unconfined compression tests of undisturbed soil. Therefore, the settlement calculation method proposed in this paper has more engineering practical value.

5. Conclusions

Based on the consideration of soft clay structure, this paper discusses the deformation mechanism of soft clay foundation in depth. Based on Hooke's law, the Duncan-Zhang model, and the step loading method, and considering the structural characteristics of soft clay, which considers the structure of the soil itself and the calculation method of the weak and soft foundation settlement, the following conclusions are obtained:

- (1) A new method for determining the deformation modulus of soft clay considering damage evolution is proposed, which provides new ideas for establishing a new method for calculating nonlinear settlement of soft clay
- (2) Based on the deformation mechanism of soft clay foundation, a calculation method of soft clay settlement based on Hook's law and the Duncan-Zhang model is established. This method requires few

parameters and provides engineering survey reports. It does not need to be determined by experiments and can provide reference for engineering practice

- (3) Through comparative analysis with a certain engineering example, the calculation accuracy of the settlement calculation method proposed in this paper can meet the actual engineering requirements, and it has certain rationality and feasibility
- (4) Though the new method has its advantages, the Duncan-Zhang model is still an elastic model with variable modulus based on incremental generalized Hooke's law, which cannot comprehensively reflect the complex characteristics of soft clay, especially the creep property. Moreover, the settlement of soft clay in practical engineering is affected by many comprehensive factors, especially geological factors. Thus, the proposed method in this paper should be modified with engineering experience

Nomenclature

List of Symbols

- σ_1 : Vertical stress of soil mass
 σ_3 : Confining pressure of soil
 ε_1 : Vertical strain of soil mass
 a : Triaxial test curve fitting parameters
 b : Triaxial test curve fitting parameters
 E_0 : Initial deformation modulus of soil
 R_f : Soil failure ratio or strength performance coefficient
 c : Cohesion of soil mass
 φ : Internal friction angle of soil
 s_i : The total compressive deformation of i layer soil
 s'_i : Deformation of the i layer soil under volumetric stress 3
 s_i'' : Deformation of soil mass under the action of deviatoric stress ($\sigma_1 - \sigma_3$)
 N_f : The number of layers of foundation compressible layers
 D_i : Thickness of i layer soil
 D : Damage variable
 ε_v : Volumetric strain
 E_m : The turning point porosity ratio when the undisturbed soil compression curve and the remolded soil compression curve are roughly parallel in the lateral compression test
 e_0 : Initial porosity of soil
 γ_t : The gravity of the t layer soil
 d_t : The thickness of the t layer soil
 σ_{3i} : The lateral stress of the i layer soil element
 σ_{1i} : The vertical average gravity stress of the i layer soil element
 k_0 : The lateral pressure coefficient
 μ : Poisson's ratio of the soil
 N : The number of loading stages
 σ_{3ij}^v : Represent the stress increment caused by the j gravity volumetric stress

- $\sigma_{(1-3)ij}^p$: The gravity partial stress of the i soil in the compressed layer
- ε_{3ij}^v : The strain under the j gravity volumetric stress
- $E_{i(j-1)}$: The deformation modulus of the i layer soil after the $(j-1)$ level self-gravity stress
- E_{ij} : The deformation modulus of the i layer soil at the j grade gravity volumetric stress.

Data Availability

The [Data Type] data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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