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Abstract: The compression and shear behavior of reconstituted clay are closely related to the initial water content of the reconstituted soil. It is difficult to obtain the compression and shear test data of clay with a high initial water content. This study aims to propose a model to predict the compression deformation and strength characteristics of reconstituted clay prepared with any initial water content using less data. Based on the concept of the disturbed state, this paper establishes a mathematical model that can simulate the compression and triaxial shear characteristics of reconstituted clay with different initial water contents. This model uses three compression curves of reconstituted clay with different initial water contents to calibrate the model parameters, and can predict the compression deformation characteristics of reconstituted clay prepared with any initial water content. The model can simulate the consolidated undrained shear behavior of clay reconstituted with different initial water contents. Comparing the measured data shows that the model is in good agreement with the measured compression curve and the triaxial stress-strain curve. The error of the predicted pore ratio and test pore ratio before yield is within 5%, and the error of the predicted pore ratio and test pore ratio after yield is within 10%. The stress-strain relationship of clay hardening with different water contents can be captured. The model can provide a preliminary prediction for the mechanical properties of clay with a high initial water content.

Keywords: high initial water content; reconstituted clay; disturbed state concept; uniaxial compression; triaxial shear; constitutive model

1. Introduction

In coastal cities, due to the shortage of land resources, many infrastructures (such as buildings, roads, railways, tunnels, and bridges) are reclaimed from the sea and built on reconstituted clay foundations [1]. The long-term stability and sustainability of these structures are closely related to the deformation and strength of soft soil, so it is necessary to accurately characterize the strength and deformation characteristics of soft soil to ensure the sustainability requirements of construction structures. The nature of natural sedimentary soil differs from that of reconstituted clay is called the "inherent property" of cohesive soil [2]. Therefore, the evolution of the mechanical properties of reconstituted clay can be used to evaluate the mechanical properties of undisturbed natural soil [3]. The compression characteristics of reconstituted clay not only depend on the liquid limit of clay but are also closely related to the initial water content of the prepared reconstituted clay. The higher the initial water content, the higher the compression [4–11].

Generally, the *e*-lg*p* compression curve of soft structural soil shows an inverse "S" shape with structural yield pressure. The *e*-lg*p* inverse "S" curve of reconstituted soft soil



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with a high initial water content has been reported in the literature [2,4–7,9], indicating that reconstituted clay with a high water content has yield pressure, and also has "structure". This existed reconstituted yield pressure has been attributed to the effect of moisture tension [12]. Some methods for studying structural natural clays are still applicable for studying reconstituted clays with a high water content. Liu et al. [13] proposed a conceptual compression model for the disturbed state of structural clay, which can be well used to describe the characteristics of structural soil under initial yield, rebound, and reloading. Quria et al. [14] used the concept of the disturbance state to describe the change of the isotropic compression index of structural soil between the relatively complete state and the fully adjusted state, which is used to predict the compression behavior of structural soil and the triaxial shear behavior of low-overconsolidation-ratio clay. There are many achievements in using the concept of the disturbed state to quantitatively study the compression and shear properties of structured natural clay. However, there are few reports on using the concept of the disturbed state to study the compression and shear properties of structured natural clay.

There are few works of literature on the quantitative study of the influence of the initial water content on the compression characteristics of reconstituted clay. Zeng et al. [15] evaluated the influence of the initial water content on the compression characteristics of reconstituted clay in detail by comparing the difference between reconstituted and natural clay compression curves with the same initial water content. Zeng et al. [16] proposed a three-parameter compression model to describe the compression characteristics of dredged soil, and the model prediction meets with the test results. However, these models are not extended to simulate the triaxial shear properties of reconstituted clay with a high water content. Bian et al. [17] studied the change rule of the critical state line of reconstituted clay with the initial water contents. They found that the critical state line of reconstituted soil with a lower initial water content is located above the critical state line of reconstituted soil with a higher initial water content. The critical state stress ratio M is linearly decreasing with the increase of the initial water content. Lin et al. [18] studied the influence of the initial water content on the compression and strength characteristics of the hydraulic fill. They found that, with the increase of the initial water content, the compression index of the Cambridge model λ and critical state stress ratio M was increased. The current research shows that few methods have been proposed to describe the evolution of the shear properties of reconstituted clay with different initial water contents under a high water content.

The concept of the disturbed state is used to describe the "structural" change of reconstituted soft soil with a high initial water content during compression and shear. The disturbance function is established by using the change of the compression index between the complete and fully adjusted states during compression to simulate the compression characteristics of reconstituted soft soil with a high initial water content. The change of the compression index is further introduced into the modified Cambridge model. The yield pressure, elastic index, and disturbance function in the model are all related to the initial water content of the soil. The relationship between these characteristic parameters and the initial water content function is established to describe the mechanical characteristics of the reconstituted soft soil with a high initial water content in the process of compression and shear.

2. Compressive Model of Reconstituted Clay with Different Water Contents

2.1. Research on Key Parameters of Reconstituted Clay Compression Model

Butterfield et al. [19] proposed the ln (1 + e) - lgp double logarithmic co-ordinate method [4–6,9,20]. The ln (1 + e) - lgp relationship curve shows a straight line after the yield point, which means that the *e*-lgp relationship curve shows an inverse "S" curve after the yield point. The compression index is the largest at the yield point (*P* = *P*r), which decreases gradually with the increase of p and tends to stabilize after reaching a certain

value. When the compression index reaches a stable value, it corresponds to the complete loss of soil structure.

Using the concept of the disturbed state [13,14,21], the compression index of reconstituted soil with a high water content in any state between the relatively intact state (*RI*) and the fully adjusted state (*FA*) can be expressed by the following equation:

$$C_{C(a)} = (1 - D)C_{C(RI)} + DC_{C(FA)}$$
(1)

where $C_{\rm C}$ is the compression index, *D* is the disturbance function, and subscripts a, *RI*, and *FA*, respectively, represent the observed, relatively intact, and fully adjusted state.

According to Equation (1):

$$D = \frac{(C_{C(RI)} - C_{C(a)})}{(C_{C(RI)} - C_{C(FA)})}$$
(2)

where D = 0 indicates that the soil is in a relatively intact state, that is, the soil is in the state before yielding; and D = 1 indicates that the soil is in a fully adjusted state, that is, the state when the soil structure is completely destroyed. The whole process D meets the requirements of $0 \le D \le 1$. The greater the D, the higher the degree of soil structure destroyed (Figure 1).





Figure 1. Relatively intact state (RI), observed state, and fully adjusted state (FA) of the reconstituted soil with high water content.

This paper presents four kinds of reconstituted clays with different initial water contents, including Lianyungang clay, Kemen clay, Baimahu clay, and Huaian clay in Hong et al. [5] and Zeng et al. [6], which are selected as the research objects. The basic physical properties of these reconstituted clays are shown in Table 1. The clay mineral compositions of these clays are shown in Table 2. That of Huaian clay was not reported. Since the rate of de-structuring of structural soil can be expressed by the exponential power relationship between the pore ratio increment and pressure [3], this paper also takes the relationship between the disturbance function equation 1 - D and P/Pr of reconstituted soil with its water content, expressed by a power exponent (Equation (4)). Due to space limitations, four types of reconstituted clay are fitted by selecting one reconstituted clay with its initial water content (Figure 2 and Table 3). In this paper, the compression index at the maximum pressure point of each clay compression test is selected as the fully adjusted compression index. The disturbance function equation 1 - D approaches 0 at the maximum pressure

point of the compression test. Due to the power exponential function's limitations, the fitting effect is not good near the maximum pressure point of the compression test. In general, the fitting value is in good agreement with the experimental value, indicating that the power exponential function is reasonable for use in describing the disturbance function.

$$\frac{(C_{C(a)} - C_{C(FA)})}{(C_{C(RI)} - C_{C(FA)})} = (p/pr)^b$$
(3)

Soil	Density of Soil Particles (Mg/m ³)	Liquid Limit $w_{\rm L}$ (%)	Plastic Limit (%)	Reference
Lianyungang clay	2.71	74	33	Hong et al. [5]
Baimahu clay	2.65	91	38	Hong et al. [5]
Kemen clay	2.67	61	30	Hong et al. [5]
Huaian clay	2.70	100.0	38.8	Zeng et al. [6]

Table 1. Basic physical properties of reconstituted clays.

Table 2. Clay mineral compositions.

Soil	Illite	Chlorite	Kaolinite	Smectite	Reference
Lianyungang clay	60	19	13	8	Zeng et al. [22]
Wenzhou clay	65	17	11	7	Hong et al. [23]
Kemen clay	54	15	16	15	Hong et al. [23]



Figure 2. The power function relationship of compression index of reconstituted soil with high water content.



Figure 3. Relationship of structural yield stress *P*r against $e_0/e_{\rm L}$.

Figure Numbers	Soil Type	Fitting Equation	R ²
	Liangyungang clay	$(C_{\rm C}({\rm a}) - C_{\rm C}(FA))/(C_{\rm C}(RI) - C_{\rm C}(FA)) = 1.07(P/Pr) - 0.32$	0.95
Figure 2	Baimahu clay	$(C_{\rm C}({\rm a}) - C_{\rm C}(FA))/(C_{\rm C}(RI) - C_{\rm C}(FA)) = 1.13(P/Pr) - 0.38$	0.94
	Huaian clay	$(C_{\rm C}(a) - C_{\rm C}(FA))/(C_{\rm C}(RI) - C_{\rm C}(FA)) = 1.13(P/Pr) - 0.26$	0.96
Figure 3	Liangyungang clay Baimahu clay Huaian clay	$p_r = 5.67 (rac{e_0}{e_L})^{-2}$	0.95
	Liangyungang clay	$b = 0.34(e_0/e_L) - 0.34$	0.84
Figure 4	Baimahu clay	$b = 0.35(e_0/e_L) - 0.39$	0.92
0	Huaian clay	$b = 0.34(e_0/e_L) - 0.44$	0.99
	Liangyungang clay	$C_C(RI) = 0.99(e_0/e_L) - 0.33$	0.98
Figure 5	Baimahu clay	$C_C(RI) = 0.86(e_0/e_L) - 0.07$	0.98
	Huaian clay	$C_C(RI) = 0.91(e_0/e_L) - 0.02$	0.98

Table 3. Table of fitting Equations.



Figure 4. Relationship of de-structuring index *b* against e_0/e_{L} .



Figure 5. Relationship of relatively complete state compression index $C_{C(RI)}$ against e_0/e_{L} .

According to Equations (2) and (3), it can be concluded that:

$$D = 1 - \left(\frac{p}{pr}\right)^b \tag{4}$$

where *b* is a parameter that quantitatively describes the rate of de-structuring, called the de-structuring index.

According to the characteristics of the compression curve, the change of the void ratio of reconstituted clay with a high water content under an oedometer test is expressed in incremental form based on the disturbed state model, as follows:

$$de = \begin{cases} -\frac{kdp}{p\ln(10)} & p < p_r \\ -\frac{C_{C(a)}dp}{p\ln(10)} & p \ge p_r \end{cases}$$
(5)

where *k* is the elastic index of the soil, that is, the slope before the yield point of the e-lgp curve of reconstituted clay with a high water content.

2.2. Compressive Model of Reconstituted Clay with Different Water Contents under High Water Content

Hong et al. [5,20] put forward that the liquid limit void ratio $e_{\rm L}$ is a useful indicator for various reconstituted clays with a high water content, which can normalize the relationship between e_0 and the yield pressure Pr. Figure 3 shows that the yield pressure Pr and $e_0/e_{\rm L}$ of three different reconstituted clay structures have a good power exponential relationship under different initial water contents, which can be expressed by the following equation:

$$p_r = 5.67 \left(\frac{e_0}{e_L}\right)^{-2} \quad \mathbf{R}^2 = 0.95$$
 (6)

Figure 4 shows that, in the result of three different reconstituted clays with different initial water contents, the study found that the de-structuring index *b* and e_0/e_L have a good power exponential relationship. The fitting results are shown in Table 3, which can be expressed by the following equation:

$$b = b_L \left(\frac{e_0}{e_L}\right)^{a_1} \tag{7}$$

where b_L is the de-structuring index of reconstituted clay under the liquid limit water content, and a_1 and b_L are obtained by fitting the experimental data.

Figure 5 shows that, in the result of three different reconstituted clays with different initial water contents, it is found that the relative integrity compression index $C_{C(RI)}$ has a good linear relationship with e_0/e_L . The fitting results are shown in Table 3, which can be expressed by the following equation:

$$C_{C(RI)} = a_2(\frac{e_0}{e_L}) + a_3 \tag{8}$$

where a_2 and a_3 are obtained by fitting the experimental data.

Figure 6 shows that, in the result of three different reconstituted clays with different initial water contents, it is found that the void ratio e_r at the yield point has a good linear relationship with e_0 , which can be expressed by the following equation:

$$e_{\rm r} = 0.79e_0 + 0.34$$
 ${\rm R}^2 = 0.99$ (9)

Figure 7 shows that the void ratio $e_{0.5}$ and e_0 at the vertical pressure of 0.5 kPa have a good linear relationship under different initial water contents of three different reconstituted clays, which can be expressed by the following equation:

$$e_{0.5} = 0.93e_0 + 0.11 \quad \mathbf{R}^2 = 0.99 \tag{10}$$

According to the definition of the elasticity index, the elasticity index can be expressed by the following equation:

$$k = \frac{(e_{0.5} - e_{\rm r})}{\lg(2p_r)} \tag{11}$$

Substitute Equations (4), (6), (7) and (8) into Equation (1), and we can obtain:

$$C_{C(a)} = (p/pr)^{\mathsf{D}}C_{C(RI)} + (1 - (p/pr)^{\mathsf{D}})C_{C(FA)}$$
(12)



Figure 6. The relation between e_r and e_0 .



Figure 7. The relation between $e_{0.5}$ and $e_{0.5}$

Substitute Equations (11) and (12) into Equation (5) to obtain the general form of the reconstituted clay compression model with different water contents under a high water content.

2.3. Parameter Determination

 e_0 and e_L can be obtained by drawing three-phase sketches of the initial water content, liquid limit, and specific gravity, respectively, so there are five parameters to be determined for the compression model, namely, a_1 , b_L , a_2 , a_3 , and $C_{C(FA)}$. All parameters can be obtained by simple oedometer tests.

 $C_{C(FA)}$ is the compression index of complete failure of the structure. Since the compression index of reconstituted clay decreases under compression pressure, the compression index under maximum pressure is taken as the compression index of complete failure of the structure. Lianyungang clay, Baimahu clay, and Huaian clay take the compression index under the pressure of 1600 kPa as the compression index of complete structural destruction. According to the characteristics of each compression curve, the complete failure compression index $C_{C(FA)}$ of the same group of soil structures is obtained by the linear interpolation or extrapolation method for the complete failure compression index of reconstituted clay structures with known water contents.

This model can simulate the compression characteristics of reconstituted clay with different water contents. The established model is relatively intuitive, and all model parameters are determined by conventional oedometer tests.

3. Modified Cambridge Model of Reconstituted Clay with High Water Content Considering Structure

The modified Cambridge model adopts the relevant flow rule that the yield function f is equal to the plastic potential function g, which satisfies the equation:

$$f = g = q^2 + Mp - M^2 p_c p = 0$$
(13)

where *p* is the average principal stress, *q* is the deviator stress, *M* is the stress ratio of *q*-*p* plane critical state, and p_c is the preconsolidation pressure.

The flow rule is as follows:

$$d\varepsilon_v{}^p = \Lambda \frac{\partial g}{\partial p} \tag{14}$$

where $d\varepsilon_V^p$ is the increment of the plastic volumetric strain, Λ is the plastic scalar factor, and $\partial g/\partial p$ is the flow direction of the plastic volumetric strain.

The dilatancy equation [24] is as follows:

$$\frac{d\varepsilon_v{}^p}{d\varepsilon_d{}^p} = \frac{M^2 - \eta^2}{2\eta} \tag{15}$$

Among them, $\eta = q/p$, and $d\varepsilon_d^p$ is the plastic shear strain increment.

The hardening rule based on the concept of the disturbance state can be expressed as follows:

$$\frac{dp_c}{p_c} = \frac{1+e_0}{\lambda-k} \tag{16}$$

$$\Lambda = 0.434C_{c(a)} = 0.434\left[(1-D)C_{C(RI)} + DC_{C(FA)}\right]$$
(17)

where λ is the isotropic consolidation parameter.

According to Equations (13)–(16), the plastic volumetric strain increment $d\varepsilon_v^p$ and plastic shear strain increment $d\varepsilon_d^p$ are calculated as follows:

$$d\varepsilon_v^{\ p} = \frac{\lambda - k}{(1 + e_0)p} \left(\frac{M^2 - \eta^2}{M^2 + \eta^2} dp + \frac{2\eta}{M^2 + \eta^2} dq\right)$$
(18)

$$d\varepsilon_d{}^p = \frac{\lambda - k}{(1 + e_0)p} (\frac{2\eta}{M^2 + \eta^2} dp + \frac{4\eta^2}{M^4 - \eta^4} dq)$$
(19)

Substitute Equations (11), (12) and (17) into Equations (18) and (19) to obtain the final expression of the plastic shear strain increment $d\epsilon_V^p$ and plastic volume strain increment $d\epsilon_V^p$, respectively.

The determination method of parameters a_1 , b_L , a_2 , a_3 , and $C_{C(FA)}$ is the same as 2.2 and 2.3. The triaxial shear test model needs to determine two other parameters: Poisson's ratio v and M. Poisson's ratio of reconstituted clay is 0.3, and M is the critical state stress ratio on the *q*-*p* plane, which can be obtained by referring to the modified Cambridge model parameter M.

The triaxial shear model of reconstituted clay with different water contents has rarely been reported yet. This model can simulate the triaxial shear characteristics of reconstituted clay with different water contents, and the model parameters are easy to determine.

4. Comparison between Model Prediction Results and Test Results

• To verify the rationality and superiority of the model in this paper, MATLAB is used to program the model: three kinds of compression curves of reconstituted soil in Lianyungang clay, Baimahu clay, and Huaian clay, and one kind of consolidated undrained compression curve in Lianyungang clay in Hong et al. [5], Zeng et al. [6], and Hong et al. [23]. Due to the lack of consolidated drained shear test data, this paper only simulates the consolidated undrained shear test curve. The model parameters *a*₁,

 b_L , a_2 , and a_3 of the three reconstituted clays can be obtained from Table 3; $C_{C(FA)}$ can be obtained from the compression curve; M is the slope of the critical state line on the q-p plane of the triaxial shear test; and the obtained model parameters are shown in Table 4.

• The comparison results of the simulation results and uniaxial compression tests of three reconstituted clays, Lianyungang clay, Baimahu clay, and Huaian clay, are shown in Figures 8–10, respectively. The solid line represents the model prediction line, and the data point represents the void ratio under different effective pressures. The test data and the model simulation results in this paper show good consistency. The comparison of the void ratio in the pre-yield stage is shown in Figure 11, and the error range is almost within ±5%. The comparison of the void ratio in the pre-yield stage is shown in Figure 12. The error range is almost within ±10%, where ep and ea are the predicted void ratios before and after yielding, respectively.



Figure 8. Comparisons of compression curves: Lianyungang clay.



Figure 9. Comparisons of compression curves: Baimahu clay.



Figure 10. Comparisons of compression curves: Huaian clay.



Figure 11. Comparisons of void ratios at the pre-yield stage.



Figure 12. Comparisons of void ratios at the post-yield stage.

Soil Type	<i>a</i> ₁	b_{L}	<i>a</i> ₂	<i>a</i> ₃	M
Lianyungang clay	-0.34	0.34	0.99	-0.33	1.40 (126.6%) 1.68 (86.6%)
Baimahu clay	-0.39	0.35	0.86	-0.07	_
Huaian clay	-0.44	0.34	0.91	-0.02	—

Table 4. The parameters of the model.

The initial moisture content is shown inside the bracket ().

The comparison results between the simulated results of reconstituted clay with different initial water contents and the triaxial consolidated undrained shear test are shown in Figure 13. The test data and the simulation results of the model in this paper show good consistency.



Figure 13. Relationships of deviator stress against axial strain for Lianyungang clay.

5. Application of Model

- Since a_1 , b_L , a_2 , and a_3 are all determined by fitting the model and test data, the curve can be better fitted by taking three pieces of water content data (preferably, the maximum, middle, and minimum water content), while $C_C(FA)$ can be obtained by the linear interpolation or extrapolation method for the complete failure compression index of the reconstituted clay structure with a known water content. By combining the parameters of the compression curve and the critical state stress ratio M and Poisson's ratio ν , the consolidated undrained shear test of reconstituted soil with different water contents can be simulated.
- To further verify the practicability of the model in this paper, the compression curve of reconstituted soil with different initial water contents in Kemen clay studied by Hong et al. [5] is quoted and compared with the curve obtained by the model in this paper. The test data with the initial water content of 43%, 80%, and 122% are selected for a fitting analysis with the model in this paper. See Table 5 for model parameters.
- The comparison results between the simulation results of reconstituted clay with different initial water contents and the oedometer test of Kemen clay are shown in Figure 14. The solid line represents the model prediction line, the dotted line represents the three selected water content compression curves as the calibration line, and the data point represents the void ratio under different effective pressures. The test data and the model simulation results in this paper show good consistency. The comparison of the void ratio in the pre-yield stage loading process is shown in Figure 15, and the error range is almost between ±5%.
- The comparison of the void ratio in the post-yield stage loading process is shown in Figure 16, and the error range is almost between $\pm 10\%$.
- The comparison results between the simulation results of reconstituted clay with different initial water contents and the triaxial consolidated undrained shear test of Kemen clay [23] are shown in Figure 17. The test data and the simulation results of the model in this paper show good consistency.



Figure 14. Comparisons of compression curves: Kemen clay.

Table 5. The parameters of the model.

Clay	<i>a</i> ₁	$b_{\rm L}$	<i>a</i> ₂	<i>a</i> ₃	М
Kemen clay	-0.45	0.43	0.41	0.02	0.81 (98%); 1.00 (83.4%) 1.32 (70.4%); 1.60 (63%)

The initial moisture content is shown inside the bracket ().



Figure 15. Comparisons of void ratios at the pre-yield stage.



Figure 16. Comparisons of void ratios at the post-yield stage.



Figure 17. Relationships of deviator stress against axial strain for Kemen clay.

6. Discussion

Although some parameters of the model are obtained by fitting and their physical meaning is not clear, this can be determined by conventional odemeter tests and triaxial shear tests. The model can simulate the compression curves of other reconstituted soils with different water contents through three compression curves of reconstituted soils with different water contents. Since it is based on the modified Cambridge model, the model cannot describe the softening phenomenon in the process of consolidated undrained shear. In addition, with the development of the consolidated drained triaxial test of reconstituted clay, the model used to simulate it will be carried out in future work.

7. Conclusions

- (1) Based on the concept of the disturbed state, the change of the compression index caused by a structural failure during compression is analyzed. According to the functional relationship between the parameters of the compression curve and the water content, the compression curve equation of reconstituted clay with different water contents is established. The changes in the compression index with the compression pressure, water content, and elastic index with the water content are introduced into the modified Cambridge model. The curve equation of the triaxial shear test of reconstituted clay with different water contents is established.
- (2) The established model is relatively simple and easy to understand, and all model parameters can be determined through conventional oedometer tests and triaxial shear tests.
- (3) The model can simulate and predict the compression curves of other reconstituted soils with different water contents through the measured data of three reconstituted soil compression curves with different water contents; in addition, by adding the critical state stress ratio *M* and Poisson's ratio *v*, the consolidated undrained shear test of reconstituted soil with different water contents can be simulated.
- (4) By comparing the test data and simulation results, it is confirmed that the established model can better simulate the compression and triaxial shear mechanical properties of reconstituted clay with different initial water contents.
- (5) Since it is based on the modified Cambridge model, the model cannot describe the softening phenomenon in the process of consolidated undrained shear. In addition, with the development of the consolidated drained triaxial test of reconstituted clay, the model used to simulate it will be carried out in future work.

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