Interpretation of mechanical behavior of cement-treated dredged soil based on soil skeleton structure

Interprétation des comportements mécaniques des sols dragués traités au ciment basée sur la structure squelette du sol

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ABSTRACT: The objective of this study was to examine the mechanical behaviors of cement-treated dredged soil and evaluate them based on action of the soil skeleton structure through simulation of the behaviors by the SYS Cam-clay model. Besides, the behaviors were simulated by the ***GEOASIA*** soil-water coupled finite deformation analysis code. The new findings are summarized as follows; 1) As the soil is treated with high cement with low initial water content under shearing in high confining stress, its effective stress path moves up closer to the tension cut-off before failure. 2) The treated soil approaches the NCL of the remolded cement-treated soil. 3) The treated soil is regarded as a high structure and overconsolidated soil. 4) FEM analysis can describe softening behavior with shear banding through the triaxial compression test.

RÉSUMÉ: L'objectif de cette étude est d'examiner les comportements mécaniques de sols dragués traités au ciment et de les évaluer sur la base de l'action de la structure de squelette du sol par la simulation des comportements à l'aide du modèle SYS Cam-clay. Par ailleurs, les comportements sont simulés par GEODESIA, un programme d'analyse de déformations finies sol-eau couplées. Les nouveaux résultats sont résumés comme suit; 1) Comme le sol est traité avec du ciment haut à teneur en eau initiale faible avec cisaillement sous contrainte de confinement élevé, son chemin de contrainte effective se déplace plus près de la tension de coupure avant la rupture. 2) Le sol traité se rapproche de la NCL du sol traité au ciment et remoulé. 3) Le sol traité est considéré comme une structure haute et surconsolidée. 4) L'analyse par éléments finis peut décrire des comportements d'adoucissement avec bande de cisaillement lors d'essai de compression triaxiale.

KEYWORDS: cement stabilization, soil skeleton structure, elasto-plastic mechanics.

1 INTRODUCTION

About 1.3 million m^3 of dredged soil is produced annually in Nagoya Bay. However, the temporary storage capacity for the soil at Nagoya Port Island (PI) is limited, so effective use of the soil as a geomaterial has become a pressing issue. The water content of the soil is high, and the unconfined compressive strength is low, so to effectively use the soil as a geomaterial, it is necessary to add a stabilizer such as cement to improve the mechanical properties. Therefore, in this study, the mechanical behavior of cement-stabilized dredged soil (hereafter referred to as treated soil) was determined using laboratory tests and reproduced using an elasto-plastic constitutive model, with the objective of explaining the improvement effect.

Past constitutive equation study into cement-stabilized soil includes, for example, the study by Hirai et al. (1989), Yu et al. (1998), Kasama et al. (2000), Lee et al. (2004), and Wada et al. (2004). This study used the SYS Cam-clay model (Asaoka et al. 2002), an elasto-plastic constitutive model based on the action of the soil skeleton structure. It was assumed that the mechanical behavior for the criteria to define the soil skeleton structure was the mechanical behavior obtained from remolded samples of treated soil (hereafter referred to as remolded treated soil). The one-dimensional compression behavior was reproduced in addition to the shear behavior in order to explain the improvement effect of adding cement based on elasto-plastic mechanics, taking the soil skeleton structure into consideration. In addition, the effect of nonuniform deformation on triaxial test results was investigated by solving as a boundary problem (Asaoka et al. 1995), taking into consideration brittle behavior, which is a characteristic of the treated soil that was observed in the tests, in addition to the constitutive equation response considering the triaxial test to be an element test.

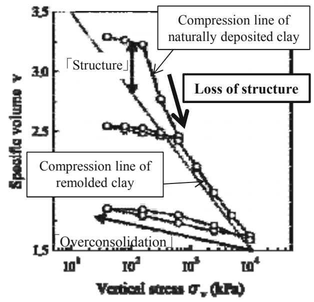

Figure 1. One-dimensional compression of natural deposited clay and definition of structure and overconsolidation

1 THE SYS CAM-CLAY MODEL

This section describes the SYS Cam-clay, the elasto-plastic constitutive model that was used to explain the mechanical behavior of the treated soil. Fig. 1 shows the oedometer test results for natural deposited clay and remolded clay. Natural deposited clay is defined as clay with structure, where the difference in specific volume v ($=1+e$; e is the void ratio) from remolded clay at the same vertical stress, in other words, the “bulk” is taken to be the extent of structure. As the vertical stress increases, the compression line of the natural deposited clay approaches that of remolded clay. The interpretation of this behavior in terms of the concept of soil skeleton structure is that there is decay/collapse of the soil structure due to shearing (plastic deformation) of the soil. A triaxial compression test is not shown here, but the critical state of natural deposited clay gradually approaches that of remolded clay as a result of shear. Basically, the structure collapses due to shear. Likewise, overconsolidation becomes normal consolidation as a result of plastic deformation. The SYS Cam-clay model defines structure, overconsolidation, and anisotropy as the soil skeleton structure, and an evolution rule is introduced that varies them in accordance with the plastic deformation to reproduce the mechanical behavior of natural deposited clay. This study focused on structure and overconsolidation, controlling the ease of change of their states using a degradation index of structure and a degradation index of OCR in accordance with their respective evolution rules (see Table 3), to explain the treated soil as natural deposited clay and the remolded treated soil as remolded soil.

Table 1 Physical properties of dredged soil

Soil particle density ρ_s [g/cm^3]	2.67
Natural water content w_n [%]	50–110
Liquid limit w_L [%]	52.5
Plastic limit w_p [%]	25.1
Plasticity index I_p [%]	27.4
Clay content [%]	60
Silt content [%]	36.6
Sand content [%]	3.4
Mean grain diameter D_{50} [mm]	0.002

2 REPRODUCTION OF THE MECHANICAL BEHAVIOR OF TREATED SOIL WITH SYS CAM-CLAY MODEL

2.1 *Physical properties of dredged soil and treated soil mixture conditions*

Table 1 shows the physical properties of PI dredged soil. Almost all of the soil is fine fraction with a high natural water content, and it does not achieve the required strength. Also, Table 2 shows the mixture conditions of the treated soil. In this study, the mixture conditions were assumed to be a water content w=120%, cement contents of C=30, 50, and 70 kg/m^3, and 28 days' curing in order to ensure fluidity and strength for the assumed Pneumatic Flow Method (Coastal Development Institute of Technology 2008).

Table 2 Mixture conditions used in the comparison of cement content

Dredged soil water content w_0 [%]	Cement content C [kg/m^3]	Water-cement ratio W/C
120	30	25.2
	50	15.0
	70	10.6

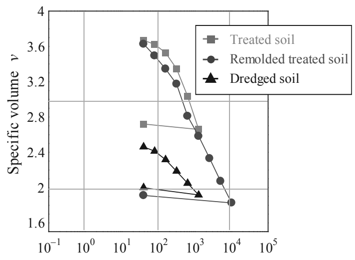

Figure 2. Comparison of uniaxial compression properties of treated soil, remolded treated soil, and dredged soil

2.2 *Mechanical behavior of treated soil (C=50 kg/m^3) and remolded treated soil and material constants*

Fig. 2 shows the oedometer test results for treated soil and remolded treated soil with C=50 kg/m^3, together with the results for dredged soil. Compared with dredged soil, treated soil has a high initial specific volume, and as a result of cement addition, it maintains the high specific volume state up to a certain vertical stress. When the vertical stress exceeds a pseudo consolidation yield stress, a high compressibility is exhibited. Compared with the remolded treated soil, there is a certain amount of structure up to the pseudo consolidation yield stress, and when the vertical stress increases further, it gradually approaches the compression line of the remolded treated soil. Fig. 3 shows the CU triaxial test results for the treated soil, and Fig. 4 shows the results for the remolded treated soil. The behavior exhibited in Fig. 3 resembles the behavior of overconsolidated and high structured clay (Asaoka et al. 2002). As shown in Fig. 4, the behavior of remolded treated soil resembles the behavior of dredged soil. However, the treated soil has a specific volume that is distinctly higher than that of dredged soil, so in Figs. 2 and 4, it is considered that remolded treated soil is a material that is different from dredged soil.

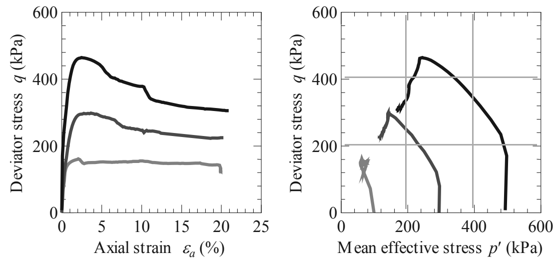

Figure 3. Consolidated undrained triaxial test results for treated soil

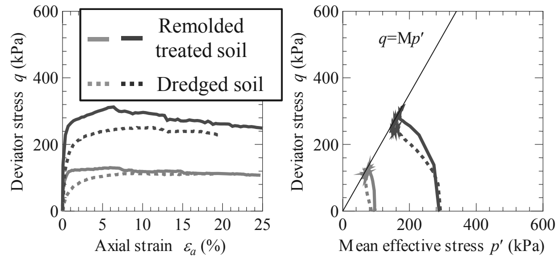

Figure 4. Consolidated undrained triaxial test results for remolded treated soil

2.3 *Reproduction of the mechanical behavior of 3 treated soils with different cement contents using the SYS Cam-clay model*

Treated soil was produced under the mixture conditions shown in Table 2, and mechanical tests were carried out on them and the remolded treated soil. Fig. 5 shows the results of oedometer tests on remolded treated soil. For all cement contents, the behavior was similar to that of remolded normally consolidated soil, and as the cement content increased, the slope of the NCL λ and the intercept N on the NCL increased. Fig. 6 shows the CU test results for remolded treated soil. For each of the cement contents, the behavior was similar to that of remolded soil, and differences in cement content did not cause a major change in the Critical state constant M. Based on the test results, the elasto-plastic parameters in accordance with the differences in cement content were assigned, as shown in Table 3.

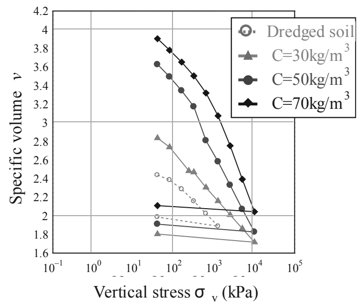

Figure 5. Standard consolidation test results for 3 remolded treated soils

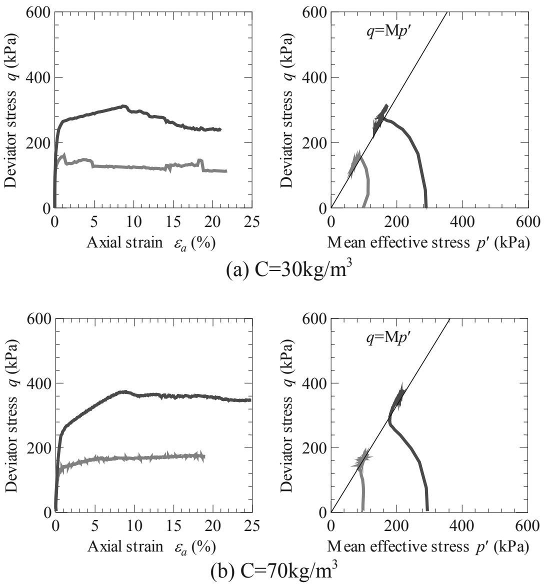

Figure 6. Consolidated undrained triaxial compression test results for remolded treated soils

Fig. 7 shows the oedometer test results for treated soil and the results reproduced using the SYS Cam-clay model. The test results show that as the cement content is increased, the consolidation yield stress increases, and in all cases, when the consolidation yield stress is exceeded, high compressibility is exhibited. For all the cement contents, it is considered that a high structure has been produced by the addition of cement. The analysis was generally capable of reproducing these trends. However, as the cement content increased, the accuracy was reduced.

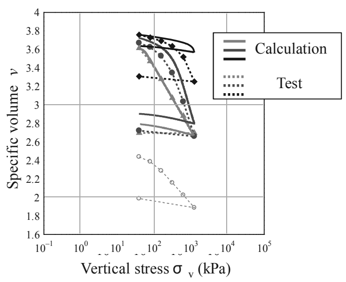

Figure 7. Treated soil standard consolidation test results and their analytical reproduction

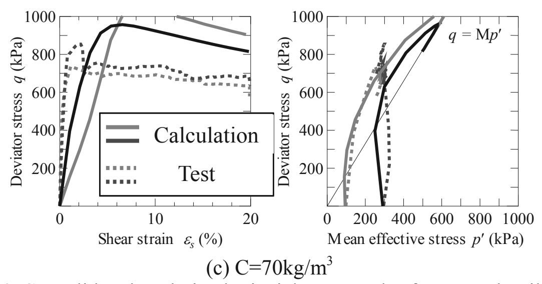

Fig. 8 Consolidated undrained triaxial test results for treated soil and their analytical reproduction

Fig. 8 shows the undrained shear test results and the reproduced results for treated soil. The critical state line CSL $q = \mathrm{M}p'$ for remolded treated soil is also shown in this figure. From the test results, the softening behavior occurs below $q = \mathrm{M}p'$ for treated soil with C=30 kg/m^3. For treated soil with C=50 kg/m^3, softening behavior occurs above $q = \mathrm{M}p'$ under high confining pressure. For treated soil with C=70 kg/m^3, there is distinct hardening behavior associated with plastic expansion and a high overconsolidation ratio. As the cement content is increased, the maximum value of the stress ratio q/p' easily exceeds M, and for C=70 kg/m^3, the effective stress reaches the tension cut-off line ($q = 3p'$). The analysis reproduced the behavior of the treated soil for low cement content, but it was difficult to reproduce the behavior above $q = \mathrm{M}p'$ for treated soil with a high cement content.

Table 3 shows the initial values of the material constants of the SYS Cam-clay model used in the analysis. The addition of cement produced high structure and pseudo overconsolidation. Also, the overconsolidation ratio increased as the cement content increased, but on the other hand, the extent of evolution of structure reduced. This is considered to be due to the fact that the water content of the dredged soil was constant in the mixture conditions used, so as the cement content increased, the water-cement ratio reduced, and this corresponds to the increase of N of the remolded treated soil as the cement content increased.

Table 3 SYS Cam-clay model material constants and initial values

Plasticity parameters		Treated soil		
Cement content (kg/m^3)		C=30	C=50	C=70
Water-cement ratio		25.2	15.0	10.6
Confining pressure (kPa)		98.1	98.1	98.1
Compression index	λ	0.21	0.36	0.51
Swelling index	κ	0.05	0.05	0.03
Limit state constant	M	1.70	1.60	1.65
NCL intercept	N	2.70	3.40	4.20
Poisson's ratio	ν	0.30	0.30	0.30
Evolution rule parameters				
Normal consolidated soil index	m	0.01	0.60	5.00
Structure degradation index	a	0.25	0.60	1.50
	b	1.00	1.00	1.00
	c	1.00	1.00	1.00
Plastic shear:plastic compression	c_s	0.20	0.50	0.10
Rotation hardening index	b_r	0.00	0.00	0.00
Rotation hardening limit index	m_b	0.50	0.50	0.50
Initial values				
Overconsolidation ratio	$1/R_0$	1.03	20.9	63.8
Extent of structure	$1/R_0$□	260	10.00	5.00
Vertical stress	σ_v	19.6	19.6	19.6
Specific volume	v_0	3.94	3.75	3.80
Stress ratio	η_0	0.00	0.00	0.00
Initial anisotropy	ζ_0	0.00	0.00	0.00

3 SOIL-WATER COUPLED FINITE DEFORMATION ANALYSIS FOR TRIAXIAL TESTS

In the above, we attempted to explain the mechanical behavior of treated soil from the point of view of considering the triaxial test as an element test. However, from observation of the failure mode of the test specimens, The characteristic brittle failure had occurred in the treated soil. Therefore, in this section, the effect of nonuniform deformation on the triaxial test results was investigated, taking the triaxial test to be a boundary problem.

3.1 *Analysis conditions for the soil-water coupled finite deformation analysis*

The soil-water coupled finite deformation analysis code ***GEOASIA*** (Noda et al. 2008), which incorporates the SYS Cam-clay model as the constitutive equation for soil structure, was used in the analysis. The analysis was carried out under plane strain conditions, and Fig. 9 shows the finite element mesh and boundary conditions. An undrained boundary was set around the test specimen, and frictional conditions were assumed at the top and bottom end surfaces with a rigid cap and pedestal. A primary asymmetric mode with a cosine curve (half period) having an amplitude of 0.005 cm (Asaoka et al. 1995) was applied as an initial geometric imperfection to the side surfaces of the test specimen. The shear velocity was 1.4×10^{-2}%/min, with a downward displacement velocity applied to the top end surface of the test specimen. The target test was C=50 kg/m^3 under confining pressure 294 kPa as shown in Fig. 3. The triaxial test was considered to be an a boundary problem, and the calculation was carried out using the material constants and initial values for the SYS Cam-clay model (Table 3).

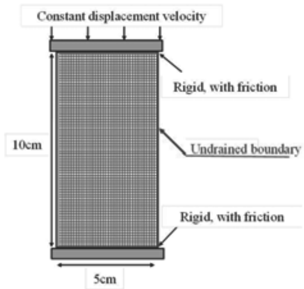

Figure 9. Finite element mesh and boundary conditions

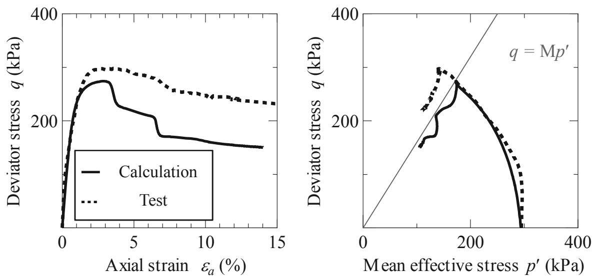

Figure 10. Consolidated undrained triaxial test results for remolded treated soil

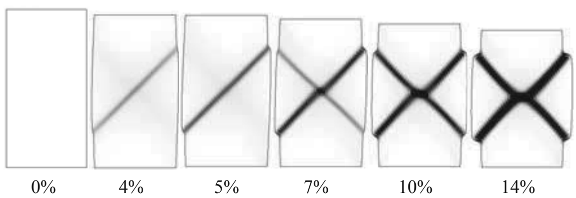

Figure 11. Consolidated undrained triaxial analysis results for remolded treated soil

Photograph 1 Failure shape of the test specimen

3.2 *Soil-water coupled finite deformation analysis results*

Fig. 10 shows the analysis results arranged considering the test specimen to be one element, together with the test results. Fig. 11 shows the shear strain distribution from the analysis. From the axial deviator stress-axial strain relationship in Fig. 10, it can be seen that at around 3% of axial strain and at around more than 6% of axial strain, the deviator stress suddenly drops. In the shear strain distribution in Fig. 11, 'diagonal shear band' occurs at about the same axial strain as in Fig. 10, then a shear band in the opposite direction occurs, and finally X-shaped shear bands are formed. The occurrence of shear bands and the drop in q coincide, so it can be seen that the cause of the drop in q is the occurrence of shear bands. In the test results, a clear load drop occurs at around 7–8% axial strain, but at around 5%, a small load drop can also be seen. Photograph 1 shows a view of the test specimen after shearing. X-shaped shear bands are formed as in the analysis.

4 CONCLUSIONS

We attempted to explain the mechanical behavior and improvement effect of treated soil due to the addition of cement based on test results, the SYS Cam-clay model, which is an elasto-plastic constitutive model that incorporates the concept of soil skeleton structure, and ***GEOASIA***. The following conclusions were obtained.

(1) Mechanical behavior of cement-stabilized treated soil: In the oedometer tests, as the cement content increased, the initial specific volume increased, the consolidation yield stress increased, and the compressibility was smaller up to the consolidation yield stress. In the triaxial tests, as the cement content increased, the maximum value of the stress ratio q/p' increased and approached the tension cut-off line.

(2) Mechanical behavior of remolded treated soil: In the oedometer tests, as the cement content increased, the intercept N and the slope λ of the NCL increased. In the triaxial tests, the M did not vary much with cement content.

(3) Reproduction using the SYS Cam-clay model: The addition of cement produces a higher structure and pseudo overconsolidation in the soil. Also, differences in cement content are easily reflected in differences in the overconsolidation ratio, and differences in water-cement ratio are easily reflected in the degree of structure. The analysis reproduced the mechanical behavior of treated soil, but for high cement contents, reproduction by analysis was difficult, which suggests that it is necessary to introduce a new model.

(4) Finite element analysis of the triaxial test: Although there were differences in the axial strain at occurrence of shear banding and the amount of drop in q, the analysis was capable of reproducing the trends of both occurrence of shear banding and the sudden drop in q. However, material constants and initial values used in the analysis were obtained by considering the triaxial test to be an element test. It is necessary to incorporate the viewpoints of both element tests and boundary problems in order to comprehend the natural behavior of the treated soil.

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