

# Study on changes in mechanical properties of mudstone due to slaking and its modelling

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**ABSTRACT:** Mudstone disintegrates after drying and wetting cycles, which is known as “slaking” and poses a threat to infrastructures that contain mudstone. In this study, consolidation undrained triaxial compression tests were conducted on fresh mudstone, remolded mudstone and mudstone after slaking to investigate the changes in mechanical properties of mudstone before and after slaking. The results indicate that slaking eliminates overconsolidation effect and reduces the stress ratio by 18% (at axial strain of 15%). Suction and saturation could be significant factors of changes in mudstone during the drying and wetting cycles. From the perspective of unsaturated soils, a modified constitutive model is newly proposed to capture the elimination of the overconsolidation effect and the reduction of the critical stress ratio by slaking.

**KEYWORDS:** Mudstone, slaking, triaxial compression test, constitutive model.

## 1 INTRODUCTION

Tertiary mudstone is widely distributed throughout Japan and has been used in numerous engineering projects. Mudstone exhibits a characteristic whereby dried mudstone disintegrates into particles during the wetting process. This phenomenon is known as slaking.

Many researchers have conducted extensive studies on the effects of slaking on mechanical properties of mudstone. Nakano et al. (1998) idealized mudstone as a heavily overconsolidated clay. John et al. (2012) pointed out that suction also plays an important role in the transformation of mudstone and soft clay. However, there is no clear discussion in the literature on the effects of suction and saturation on the changes in the mechanical properties of mudstone. Nakano and Sakai (2016) developed a SYS Cam-clay model to investigate the effects of drying-wetting cycles on crushed mudstone. However, this SYS model does not reflect the influence of suction and degree of saturation on the mechanical behavior of mudstone. The SYS model is more suitable for materials used in man-made mudstone embankments; but it does not provide sufficient support for understanding the development of natural mudstone slopes.

Therefore, this study aims to investigate the changes in the mechanical properties of mudstone before and after slaking. Additionally, a modified constitutive model considering changes in saturation is proposed to capture the effects of slaking on the reduction of overconsolidation effect and the stress ratio.

## 2 MATERIAL

The mudstone used in this study was obtained through borehole drilling from a site in northern Honshu, Japan.

In this study, mudstone after slaking was dried and subsequently crushed with a hammer and sieved through a 2 mm sieve. Basic physical tests were completed using these mudstone particles. The basic properties of mudstone are shown in Table 1. Figure 1 shows particle grading of mudstone.

Slaking test was conducted to evaluate the slaking durability of the mudstone. Two methods were used to dry the mudstone specimens. According to the Japanese Geotechnical Society standard JGS 2124 Method for Slaking Test on Rock, it requires that specimens should be dried at room temperature (set to 23°C in this test) for 24 hours, followed by drying in an oven at 40°C for 48 hours. This group was named SL.1. However, since natural conditions in ground rarely reach 40°C, a control group was established in which specimens were dried

only at room temperature (23°C), with drying time set at 1, 2, 3, 5, and 7 days. This control group was named SL.2. After the drying process, water was added to a height exceeding that of the mudstone specimen, and the changes were recorded over a 24-hour period. The condition of the mudstone at each stage was subsequently evaluated with reference to Figure 2(a).

Figure 2(b) shows the result of the slaking test. It indicates that drying time and temperature will not affect slaking of this mudstone, all specimens disintegrated into fine particles within only two hours. Compared to other mudstones (Sharma et al., 2017) in Japan, the slaking of this mudstone was strong. Taylor (1998) proposed that the breakdown of mudstone might result from the high pore air pressures generated when water penetrates into the pores of the mudstone. Combined with slaking test, it was observed that mudstone primarily lost its strength during the wetting stage.

Table 1. Physical properties of mudstone.

Parameter	Symbol	Value	Unit
Liquid limit	$w_L$	98.47	%
Plasticity index	$I_p$	66.37	-
Specific gravity	$\rho_s$	2.744	g/cm <sup>3</sup>
Initial water content	$w$	20-28	%

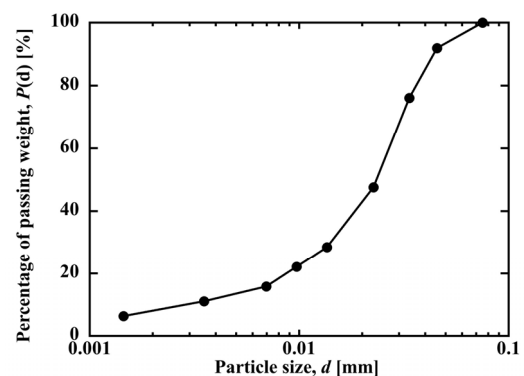


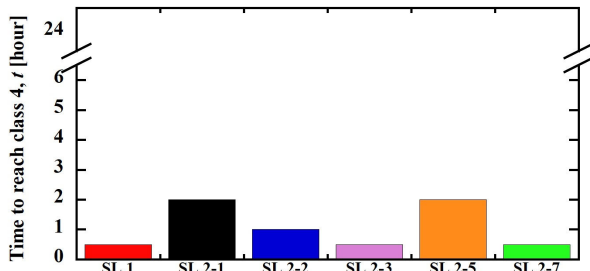
Figure 1. Particle size accumulation curve.

According to the results of XRD and SEM analyses, the mudstone contains a significant amount of montmorillonite, chlorite, and pyrite. Research conducted by Yoneda et al. (2014) has demonstrated a strong correlation between the weathering of mudstone and the reactions of these minerals. The most direct cause of macroscopic slaking is the swelling of montmorillonite upon water absorption. These findings support

the view that changes in degree of saturation are one of the primary factors influencing the mechanical strength of mudstone.

Class	0	1	2	3	4
A					
	There is no change.	Original shape remains with a few cracks.	Many cracks appear, specimen is divided into some fragments, and original shape can be recognized.	Whole body has crumbled; however, not muddy. Original shape cannot be recognized.	Whole body is muddy.

(a) Criteria for visually classifying mudstone to slaking (JGS 2124)



(b) Chart of time to reach Class 4

Figure 2. Results of slaking test.

### 3 $\bar{C}U$ TRIAXIAL COMPRESSION TEST

Consolidated undrained shear was set for this study. In the tests, the specimens were divided into three groups: undisturbed group (U), disturbed group (D), and air-dried before saturation group (A). Specimens of group U were obtained by directly trimming the rock core. Specimens of group D were prepared by layered compaction of wet mudstone particles after slaking. Specimens of group A were obtained by trimming the rock core, followed by air-drying for 3 days. Subsequently, the specimens were placed in a water tank under constrained lateral deformation and subjected to vacuum saturation for 3 days. Based on the results of the slaking tests, this process is sufficient to be considered as mudstone specimens after slaking. In this study, confining pressure of 100, 150, and 200 kPa was set. Figure 3 shows the results of the triaxial tests.

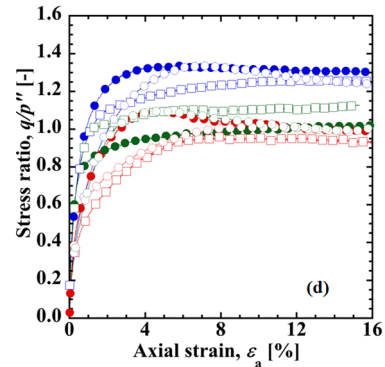
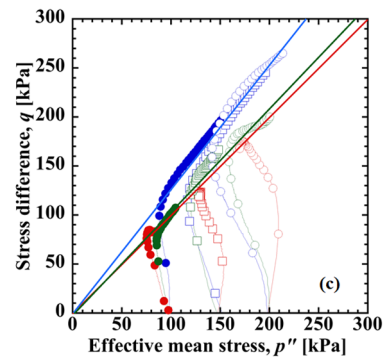
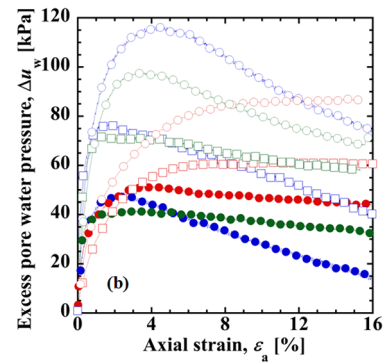
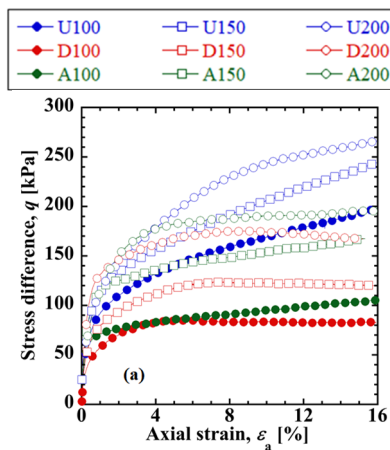


Figure 3. Results of triaxial tests: (a) relationship between stress difference and axial strain, (b) excess pore water pressure and axial strain, (c) stress ratio and axial strain, (d) stress difference and effective mean stress.

From The results show that after a single wetting–drying cycle, the dilative behavior exhibited by Group A is less pronounced than that of Group U, indicating that slaking has reduced the overconsolidation effect. Moreover, the critical stress ratio decreases by 18%.

### 4 ELEMENT SIMULATION

Slaking has been shown to reduce both the critical stress ratio and the overconsolidation effect of mudstone, as revealed by triaxial test results. However, existing constitutive models do not adequately reflect this degradation, particularly the decline in critical stress ratio. To address this, this study aims to develop a new constitutive model based on Zhang and Ikariya (2011)'s unsaturated soil model.

This study incorporates  $\xi$  as a state variable to control the weakening from slaking. Equations (1)-(3) are modified yielding functions, incorporating  $\xi$  into the stress ratio. Due to the influence of slaking, critical stress ratio changes accordingly, as demonstrated by the test results. Where  $\rho_s$  and  $\rho_e$  are the state variable of saturation and overconsolidation.  $\lambda$  is compression index and  $\kappa$  is swelling index.

$$f = f_\sigma + \frac{\rho_e - \rho_s}{1 + e_0} \frac{1}{C_p} - \varepsilon_v^p \frac{1}{C_p} = 0 \quad (1)$$

$$C_p = \frac{\lambda - \kappa}{1 + e_0} \quad (2)$$

$$f_\sigma = \ln \frac{p}{p_0} + \ln \frac{M^2 + \eta^2 - \xi^2}{M^2 - \xi^2} \quad (3)$$

From consistency equation  $df = 0$ :

$$df = \frac{\partial f_\sigma}{\partial \sigma_{ij}} d\sigma_{ij} + \frac{\partial f}{\partial \rho_e} d\rho_e - \frac{\partial f}{\partial \rho_s} d\rho_s - \frac{\partial f}{\partial \varepsilon_v^p} d\varepsilon_v^p = 0 \quad (4)$$

Associate flow rule:

$$d\varepsilon_{ij}^p = \Lambda \frac{\partial f}{\partial \sigma_{ij}} \quad (5)$$

$M$  is the critical stress ratio,  $e_0$  is the initial void ratio, and  $\varepsilon_v^p$  is the plastic volumetric strain. The following Equations (6)-(13) are evolution equations. Based on extensive experimental investigations, Zhang and Ikariya (2011) identified the void ratio, skeleton stress tensor, and degree of saturation as independent state variables controlling the mechanical behavior of unsaturated soils. The relationships among these variables explicitly account for the influence of saturation on the constitutive behavior.

$$N(S_r) = N + \frac{N_r - N}{S_r^s - S_r^r} (S_r^s - S_r) \quad (6)$$

$$N_r = N(S_r^r) \quad (7)$$

$$\rho_s = N(S_r) - N = Q(S_r^s - S_r) \quad (8)$$

$$Q = \frac{N_r - N}{S_r^s - S_r^r} \quad (9)$$

$$d\rho_s = -Q dS_r \quad (10)$$

Where  $N$  is the void ratio at the normally consolidated line under saturated conditions at a mean effective stress of  $p' = 98$  kPa, and  $N_r$  is the void ratio on the normally consolidated line under unsaturated conditions under the reference mean skeleton stress when the degrees of saturation is in residual state, that is,  $N_r = N(S_r^r)$ .  $S_r$  is the degree of saturation,  $S_r^r$  is the residual degree of saturation, and  $S_r^s$  is the degree of saturation under full saturation. Equation (6) means that  $N(S_r)$  changes linearly with the degree of saturation.

The change in overconsolidation effect depends on the initial state and mean stress, and in this study it is also considered to be affected by saturation changes during wetting.

$$d\left(\frac{\rho_e}{1 + e_0}\right) = -\Lambda \frac{\rho^\beta}{p} + \frac{n_1 * \rho}{1 + \exp(-mdS_r)} * dS_r \quad (11)$$

$$\rho = a\rho_e + b\rho_s \quad (12)$$

Equation (13) represents the weakening effect caused by slaking, which is related to the increment in saturation. During the wetting phase,  $\xi$  rises rapidly, achieving the weakening effect.

$$d\xi = \frac{n_2 * (M^2 - \xi^2 - M_{SL}^2)}{1 + \exp(-mdS_r)} * dS_r \quad (13)$$

Volumetric strain increment can be divided into elastic and plastic part as,

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p \quad (14)$$

Using Hooke's theory with stiffness tensor  $E_{ijkl}$ , incremental stress tensor can be expressed as,

$$d\sigma_{ij} = E_{ijkl}(d\varepsilon_{kl} - d\varepsilon_{kl}^p) = E_{ijkl}d\varepsilon_{kl} - E_{ijkl} \Lambda \frac{\partial f}{\partial \sigma_{kl}} \quad (15)$$

Substituting this into Equation (4), the relation can be as:

$$\Lambda = \frac{\frac{\partial f}{\partial \sigma_{ij}} E_{ijkl} d\varepsilon_{kl} + \frac{1}{C_p} \frac{Q}{1 + e_0} dS_r}{\frac{1}{C_p} \left( \frac{\partial f}{\partial \sigma_{mm}} + \frac{\rho^\beta}{p} \right) + \frac{\partial f}{\partial \sigma_{ij}} E_{ijkl} \frac{\partial f}{\partial \sigma_{kl}}} \quad (16)$$

It can be defined as:

$$\begin{aligned} \Lambda > 0 & \text{ loading,} \\ \Lambda = 0 & \text{ neutral,} \\ \Lambda < 0 & \text{ unloading} \end{aligned} \quad (17)$$

Table 2 presents the parameters of the mudstone material, while Table 3 shows the initial value of state variables used in the element simulation. In this study, the parameters were obtained through testing, with clear physical significance assigned to each.

Table 2. Material parameters.

Parameter	Symbol	Value
Compression index	$\lambda$	0.065
Swelling index	$\kappa$	0.035
Critical state parameter	$M$	1.268
Poisson's ratio	$\nu$	0.100
Void ratio	$N$	0.867
Void ratio	$N_r$	0.932
Parameter of overconsolidation	$a$	3
Parameter of overconsolidation	$b$	1
Parameter of suction	$\beta$	1
Parameter of slaking	$n_1$	0.2
Parameter of slaking	$n_2$	2
Parameter of development of $\rho_e$ and $\xi$	$m$	6000
Critical stress ratio after slaking	$M_{SL}$	0.972

The relationship between suction and saturation in the simulated drying-wetting cycle of group A was determined using the results of filter paper method (D5298-03 ASTM international) and fitted using the water retention curves model from Zhang and Ikariya (2011). The results are shown in Figure 4. The primary range of the WRC occurs at degrees of saturation between 0.1 and 0.85, as identified from the slaking test.

Table 3. Initial value of state variables.

Initial value	Confining pressure	Group		
		U	D	A
$\rho_e$	-	0.050	0.020	0.050
$\xi$	-	0.000	0.814	0.000
$e$	100 kPa	0.799	1.056	0.716
	150 kPa	0.731	0.835	1.019
	200 kPa	0.585	0.868	1.020
$\rho_s$	-	0.000	0.000	0.000

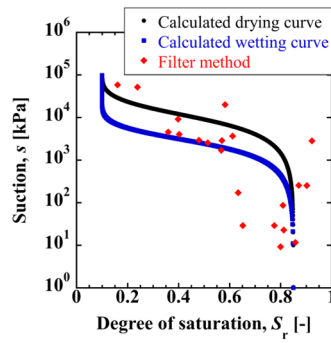


Figure 4. Water retention curves.

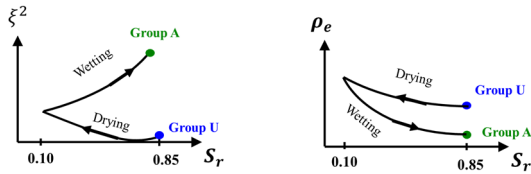


Figure 5. The relation between  $\xi^2$ ,  $\rho_e$  and saturation.

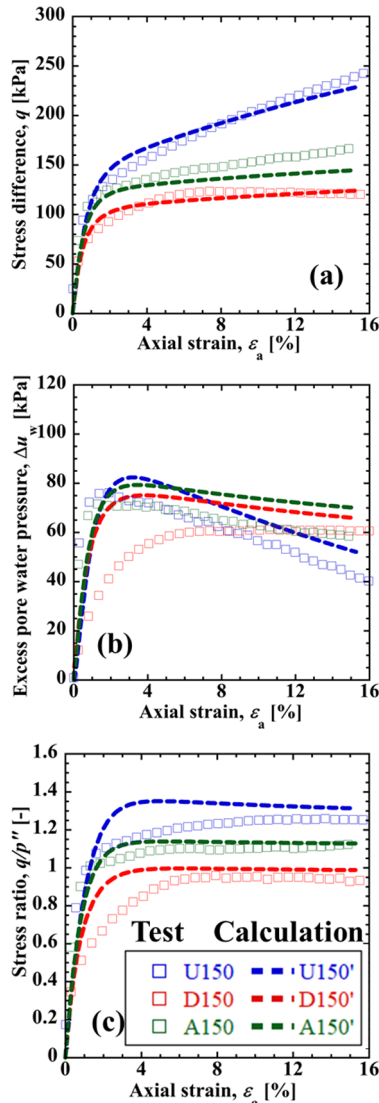


Figure 6. Triaxial test and calculation results in 150 kPa confining pressure: (a) relationship between stress difference and axial strain, (b) excess pore water pressure and axial strain, (c) stress ratio and axial strain.

In this study, group D has the largest weakening effect from slaking; therefore, the initial values of  $\xi$  and  $M_{SL}$  are determined from group D results. In the simulation, groups U and A initially represent fresh mudstone that has not undergone slaking, meaning  $\xi$  is set to zero, and the overconsolidation parameters are equal. Subsequently, group A undergoes one drying-wetting cycle before being shearing, whereas groups U and D are directly sheared in a saturated state. During the drying-wetting process, the net stress remains unchanged, while the degree of saturation decreases from 0.85 to 0.1 and then increases back to 0.85, and returns to full saturation before shearing.  $\xi^2$ ,  $\rho_e$  changes with saturation are demonstrated by Figure 5. The change in saturation changes the value of  $\xi$ , reducing the overconsolidation effect and critical stress ratio.

Figure 6 shows the experimental (point) and calculated (linear) results for a confining pressure of 150 kPa. The result shows that the proposed model effectively captures the effect of slaking on mudstone after a drying-wetting cycle, as evidenced by a significant decrease in the critical stress ratio at 15% axial strain and a reduction in overconsolidation effect.

## 5 CONCLUSIONS

In this study, slaking tests and  $\overline{CU}$  tests were conducted on mudstone. Based on the results of triaxial tests, a constitutive model was developed to simulate the effect of slaking on the mechanical properties of mudstone from an unsaturated soil perspective.

1. Variations in drying conditions and duration do not affect the slaking characteristics of the mudstone, as the vast majority of samples disintegrate into small particles within two hours.
2. In the  $\overline{CU}$  tests, three different states of mudstone specimens were used. Among them, the mudstone that underwent one drying-wetting cycle exhibited a significant decrease in critical stress ratio and overconsolidation effect.
3. The newly developed constitutive model effectively captures the effect of slaking on the stress ratio and overconsolidation critical of mudstone.

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