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Interpreting the Slaking Mechanism of Soft Rock Using a Coupled Hydro-Mechanical Model

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Abstract

The long-term deterioration of soft rocks such as mudstone due to slaking - a weathering process induced by repeated wetting and drying - has become a serious geotechnical and safety issue in Japan, as it can eventually lead to the failure of embankments composed of soft rock fragments over several decades.

In this study, a new numerical model was developed to simulate the slaking behavior of soft rock, aiming to predict long-term extent and rate of weathering. Swelling of clay minerals has been identified as one of the potential causes of slaking. To examine this mechanism, the present work assumes that water infiltrating into the rock through unsaturated flow locally induces the swelling of clay minerals, generating stress that results in rock expansion or failure. Before investigating the overall compression behavior of an embankment, the slaking behavior of individual rock fragments composing the embankment is analyzed. For simplicity, the rock was idealized as a porous sphere, and the governing equations for water mass conservation and force equilibrium were derived in one-dimensional radial form. Bishop's effective stress equation for unsaturated soils was extended by introducing a swelling pressure assumed to vary linearly with the degree of saturation, and the mass conservation and force equilibrium equations were solved in a coupled manner.

Using the proposed model, the water absorption behavior of uniformly unsaturated rock was analyzed through finite element simulation. The results demonstrated that as the degree of saturation increased from the surface inward, tensile effective stress developed, inducing outward displacement corresponding to rock expansion. These findings indicate that the proposed model successfully reproduces the deformation of rock caused by water migration.

Keywords

Slaking, Weathering, Cyclic wetting and drying, Hydro-Mechanical Coupled Problem.

1 Introduction

Slaking is a weathering process where rocks disintegrate through repeated wetting and drying cycles. This phenomenon is particularly pronounced in soft sedimentary rocks such as poorly consolidated mudstone and shale. In Japan, many earth structures constructed from soft rock experience slaking-induced deterioration, including slope failures and embankment settlements. The challenge is that slaking progresses gradually over decades, making it difficult to detect and predict (Nagata et al. 2022). As aging infrastructure exceeds 50 years of service, understanding slaking mechanisms and developing predictive methods are critical issues.

In embankments composed of soft rock particles, slaking causes particle degradation, where fragments fall into voids between larger particles, leading to overall embankment compression and consequent differential settlement. However, predicting the rate and extent of degradation remains difficult due to significant variability in rock behavior; some rocks disintegrate after a single wetting-drying cycle, while others gradually fracture over multiple cycles (Kikumoto et al. 2016).

This study aims to clarify slaking mechanisms and develop a numerical model to predict long-term weathering. As a first step, this paper focuses on reproducing slaking behavior during the wetting phase by examining a single rock particle constituting an embankment. We hypothesize that swelling of clay minerals is the primary slaking process, as rocks containing expansive clay minerals exhibit severe slaking in simple immersion tests (Kojima and Saito 1984).We develop a hydro-mechanical coupled model that links water infiltration, clay swelling, and stress development within the rock microstructure. Swelling pressure is incorporated into the effective stress framework to capture the degradation mechanism. The model is validated by simulating immersion of initially unsaturated soft rock to examine whether it appropriately reproduces wetting-induced degradation.

2 Methodology

2.1 Model formulation

We focus on a single rock particle to understand the internal mechanism of slaking. To this end, inter-particle contact forces and confining pressure are not considered in this paper. We assume weakly structured mudstone containing expansive clay minerals. The rock fragment is idealized as a perfect sphere with a homogeneous interior, acting as a porous medium that is initially uniformly unsaturated. By assuming a spherical fragment, the rock response can be formulated in spherical coordinates $r\theta\varphi$ as a one-dimensional radial problem. The material follows linear elastic behavior (compression positive) with an incompressible solid phase. Water retention and hydraulic conductivity follow the van Genuchten-Mualem model (van Genuchten1980). Failure due to slaking is evaluated using the following failure function based on the Hoek-Brown failure criterion (Hoek and Brown 2019):

$$F(\sigma_1', \sigma_3') = \sigma_1' - \sigma_3' - \sigma_{\mathrm{ci}} \left[m_{\mathrm{b}} \frac{\sigma_3'}{\sigma_{\mathrm{ci}}} + s_{\mathrm{hb}} \right]^{a_{\mathrm{hb}}} \tag{1}$$

where σ_3' and σ_1' are the minimum and maximum effective principal stress, respectively, σ_{ci} is the unconfined compressive stress, and $m_{\mathrm{b}}, s_{\mathrm{hb}}$ and a_{hb} are material constant. Failure is assumed to occur when the failure function satisfies $F > 0$ at any interior point of the particle.

The assumed degradation process during wetting is as follows: immersion of an initially unsaturated fragment causes infiltration from the surface driven by pore-water pressure gradients. Local clay-mineral swelling occurs in micro-scale regions according to local saturation, generating swelling pressure. This swelling pressure affects the effective stress that deforms the rock skeleton, while deformation alters local porosity and hydraulic conductivity, feeding back to influence unsaturated infiltration. This mutual interaction is formulated as a one-dimensional hydro-mechanical coupling problem in spherical coordinates, governing the radial distribution of water and stress within the fragment. Fig. 1 schematically illustrates the hypothesized rock slaking process.

2.2 Governing equations

The governing equations are water mass conservation and force equilibrium, coupled via effective stress that accounts for clay swelling pressure. The mass conservation equation of water in a differential volume element at radius r is expressed as:

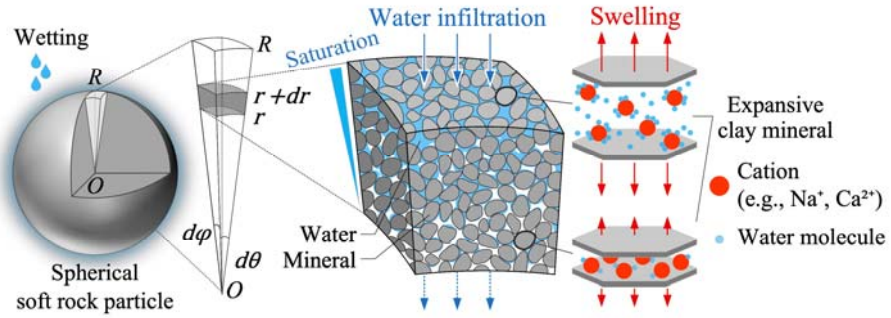


Fig. 1 Schematic overview of the proposed slaking model in this study.

$$\frac{2}{r}k\frac{\partial\psi}{\partial r}+\frac{\partial}{\partial r}\left(k\frac{\partial\psi}{\partial r}\right)=-S_{\mathrm{r}}\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}+n\frac{\partial S_{\mathrm{r}}}{\partial t} \tag{2}$$

where k is the hydraulic conductivity, ψ is the matric potential head, S_{r} is the degree of saturation, n is the porosity, and ε_{v} is the volumetric strain. The matric potential head is defined as $\psi=-(u_{\mathrm{a}}-u_{\mathrm{w}})/\gamma_{\mathrm{w}}$, where u_{a} is pore-air pressure, u_{w} is pore water pressure, and γ_{w} is the unit weight of water. In this study, u_{a} is assumed equal to atmospheric pressure and spatially uniform ($u_{\mathrm{a}}=p_{\mathrm{a}}$). The hydraulic conductivity k is expressed as the product of the saturated hydraulic conductivity $K_{\mathrm{s}}$and the relative hydraulic conductivity k_{r}, where k_{r} is determined according to saturation using van Genuchten-Mualem model.

For force equilibrium as well, we consider a differential element in the radial direction. Owing to spherical symmetry, all shear stresses vanish, and the normal stress in the radial and circumferential directions become principal stresses. Therefore, only radial equilibrium needs to be considered. The radial force equilibrium equation in terms of total stress is:

$$\frac{\partial\sigma_r}{\partial r}+\frac{2}{r}(\sigma_r-\sigma_\theta)=0 \tag{3}$$

where σ_r and σ_θ are the radial and circumferential stresses, respectively.

These two equations are coupled through an extended Bishop's effective stress equation that accounts for swelling of clay minerals. The original Bishop's equation relates effective stress σ' to total stress σ, atmospheric pressure p_{a}, and matric suction. We introduce a swelling pressure termσ_{sw}:

$$\sigma'=\sigma-p_{\mathrm{a}}-\chi\psi\gamma_{\mathrm{w}}-\sigma_{\mathrm{sw}} \tag{4}$$

where χ is a saturation-related parameter (taken as $\chi=S_r$ for simplicity). The swelling pressure is defined as a linear function of saturation:

$$\sigma_{\mathrm{sw}}=a_{\mathrm{sw}}S_r+b_{\mathrm{sw}} \tag{5}$$

where a_{sw} and b_{sw} are parameters with dimensions of stress. The parameter a_{sw} controls the swelling magnitude, while $b_{\mathrm{sw}}=-a_{\mathrm{sw}}S_{\mathrm{r0}}$ ensures that the swelling pressure is zero at the initial saturation S_{r0}. As clay minerals swell, the increasing swelling pressure reduces the effective stress within the rock, causing rock expansion and leading to failure.

To complete the formulation, the effective stress must be related to displacement through constitutive relations. Assuming linear elastic behavior, the effective stress-strain relations in spherical coordinates are expressed as:

$$\sigma_r'=\frac{E}{(1+\nu)(1-2\nu)}[(1-\nu)\varepsilon_r+2\nu\varepsilon_\theta] \tag{6}$$

$$\sigma_\theta'=\frac{E}{(1+\nu)(1-2\nu)}(\nu\varepsilon_r+\varepsilon_\theta) \tag{7}$$

where E is Young's modulus and ν is Poisson's ratio, both assumed constant during the slaking process. The volumetric strain, which appears in Eq.2 and relates mechanical deformation to water migration through porosity changes, is defined as:

$$\varepsilon_{\mathrm{v}} = \varepsilon_r + 2\varepsilon_\theta \tag{8}$$

In spherical coordinates, the radial strain ε_r and circumferential strain ε_θ are related to radial displacement u_r (positive outward) through the strain-displacement relations,

$$\varepsilon_r = -\frac{\partial u_r}{\partial r} \tag{9}$$

$$\varepsilon_\theta = -\frac{u_r}{r} \tag{10}$$

By substituting Eq.4,6,7,9, and 10 into Eq.3, the equilibrium equation written in terms of displacement is obtained and solved together with Eq.2 as a coupled hydro-mechanical system.

The negative signs arise from the stress convention (compression positive) adopted in this study. These constitutive and kinematic relations complete the coupling between hydraulic and mechanical processes: water infiltration generates swelling pressure that alters effective stress and causes deformation, while deformation modifies porosity and permeability, thereby influencing subsequent water migration.

The coupled governing equations, Eqs. 2 and 3, are solved subject to the following initial and boundary conditions. Initially, the rock is uniformly unsaturated with matric head ψ_0 (a negative constant) and zero displacement. For the water mass conservation equation (Eq.1), symmetry is imposed at the particle center ($\partial\psi/\partial r = 0$), and saturated conditions at the surface. For the force equilibrium equation (Eq.2), zero displacement is imposed at the center, and atmospheric pressure at the surface ($\sigma_r = p_{\mathrm{a}}$). These boundary conditions represent a free surface subject only to atmospheric pressure, capturing the fundamental slaking behavior of a single rock fragment. These equations are solved numerically using the finite element method with the COMSOL Multiphysics® software.

3 Results and Discussion

Using the proposed model, we simulated immersion of an unsaturated rock fragment to validate whether wetting-induced deformation and failure can be reproduced. A spherical fragment with radius $R = 5$ cm and uniform initial saturation $S_{\mathrm{r0}} = 0.91$ was analyzed. Other material properties are summarized in Table 1. The residual water content θ_{r} in the van Genuchten-Mualem model and atmospheric pressure p_{a} were set to zero.

Fig. 2 and Fig. 3 present the results of the immersion analysis. Fig. 2 shows the radial distributions of saturation, radial effective stress, and radial displacement over time. Fig. 3 presents effective stress paths at representative radial positions and the Mohr's stress circle at the failure point. Overall, water infiltrates from the surface toward the center, while tensile effective stress develops and propagates inward. The stress state first reaches the Hoek-Brown failure criterion at $t = 2302$ s and $r/R = 0.92$, indicating that the model can capture key feature of wetting-induced degradation. To inspect the subsequent response, the analysis was continued after this time until the fragment becomes fully saturated, without considering crack propagation or new failure initiation.

Table 1. Material parameters used in the analysis.

Symbol	Description	Value	Unit
E	Young's modulus	200	MPa
K_{s}	Saturated hydraulic conductivity	1e-9	m/s
a_{hb}	Hoek-Brown parameter	0.5	-
a_{sw}	Swelling parameter	3.0	MPa
m_{vg}	Van Genuchten parameter	0.7	-
m_{b}	Hoek-Brown parameter	7.0	-
n_0	Initial porosity	0.365	-
s_{hb}	Hoek-Brown parameter	1.0	-
α_{vg}	Van Genuchten parameter	0.008	1/cm
ν	Poisson's ratio	0.3	-
σ_{ci}	Unconfined compressive strength	2.0	MPa

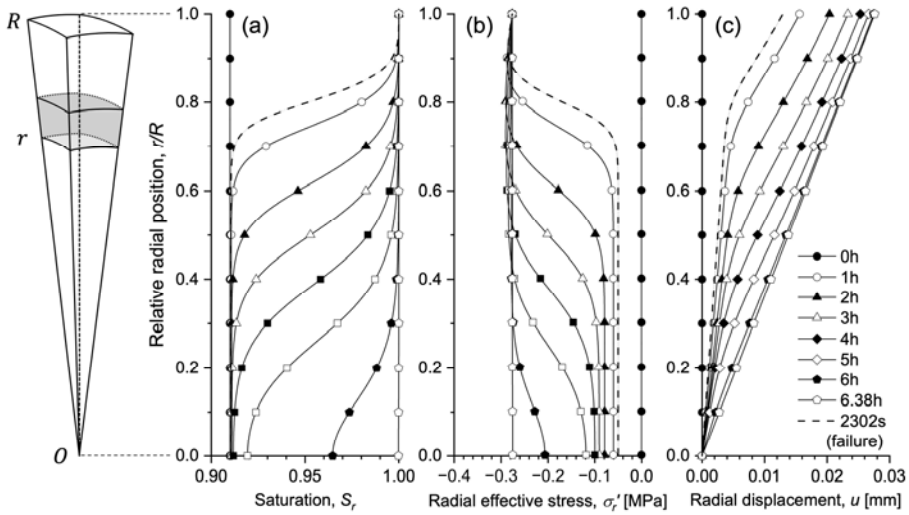


Fig. 2 Distribution of (a) saturation, (b) radial effective stress, and (c) radial displacement within a particle.

Fig.2(a) shows that the surface ($r/R = 1$) is immediately saturated with zero matric suction, and the wetting front then advances inward. At $t = 6.32$ h, saturation at the center ($r/R = 0$) reaches unity and the fragment becomes fully saturated.(b) shows that negative effective stress (tensile stress) appears first near the surface and then propagates toward the center.

When the particle interior becomes uniformly saturated, effective stress converges to the saturated swelling stress state $\sigma_{\mathrm{sat}} = a_{\mathrm{sw}}(1 - S_{\mathrm{r0}}) + b_{\mathrm{sw}}$. Fig.2(c) shows that radial displacement develops from the surface inward and becomes nearly proportional to radius at full saturation.

An interesting feature in Fig.2(b) is transient tensile stress in the outer region ($0.45 < r/R < 1$) that exceeds the final uniform value of$\sigma_r' = -0.276$ MPa. One possible interpretation is that this is analogous to thermal cracking in plate glass: the near-surface zone attempts to swell as water infiltrates, while the drier interior restrains the outer zone, generating strong tensile stress between them.

In Fig. 3(a) effective stress paths at different radial positions are shown. Because radial effective stress is always smaller than circumferential effective stress, the principal stresses are $\sigma_3' = \sigma_r'$ and $\sigma_1' = \sigma_\theta'$. At the surface ($r/R = 1$), the path quickly reaches the final radial stress and then moves downward as circumferential stress decreases. At the center ($r/R = 0$), applying l'Hôpital's rule in the definition of circumferential strain gives $\varepsilon_\theta = \varepsilon_r$. Substituting this into the effective stress definitions yields $\sigma_r' = \sigma_\theta'$; therefore, the stress path follows the 45°line. For $0 < r/R < 1$, the stress paths lie between these two limiting paths, but, as shown in Fig. 2(b), large tensile stress exceeding the final state appears transiently in the near-surface interior. Fig. 3(b) shows the Mohr's stress circle plotted on $\sigma_n - \tau$ plane at $r/R = 0.92$where failure occurs. The position of the stress circle relative to the Hoek-Brown failure envelope indicates that the rock undergoes tensile-shear failure at this point. The angle of the failure plane measured from circumferential direction is 6.89°.

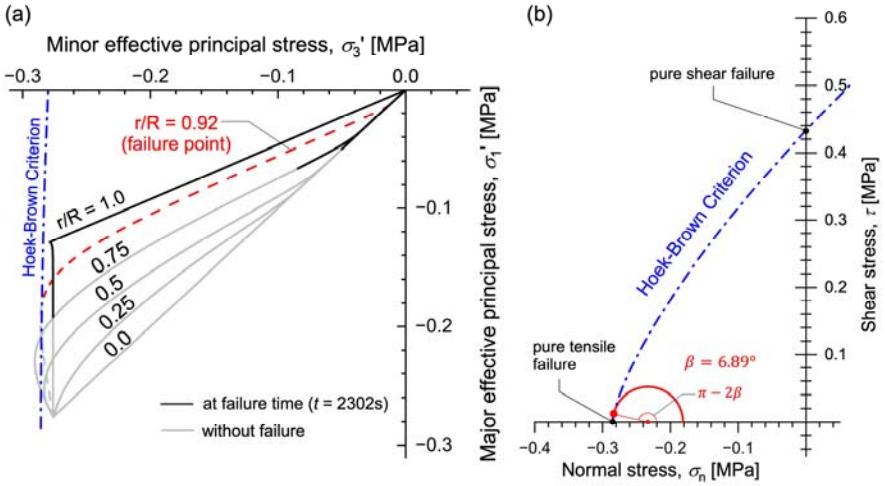


Fig. 3 (a) Effective stress paths and (b) Mohr's circle at failure point compared with the Hoek-Brown failure criterion.

For this parameter set, the stress state first reaches the Hoek-Brown failure criterion at $r/R = 0.92$. However, in the hypothetical continued analysis that neglects post-failure stress redistribution, even larger tensile stress develops at $r/R = 0.75$, which is deeper below the rock surface. These results indicate that when and where the failure criterion is reached is governed by the relative position of the stress paths to the failure envelope. In this case, failure initiates about 38 min after immersion at a shallow subsurface position, consistent with layered exfoliation observed in simple slaking tests. If swelling potential is higher or rock strength is lower, earlier failure near the surface would be expected, potentially reproducing rapid mud-like disintegration. Future study is needed to clarify which parameters influence the rate and mode of slaking.

4 Conclusion

This study proposes a new numerical model to describe slaking behavior, particularly slaking during the wetting process. We hypothesize that swelling of clay minerals contained within the rock is the primary slaking process and develop a coupled model that integrates water mass conservation and force equilibrium within the rock. Using the proposed model, we simulated immersion of initially uniformly unsaturated soft rock and demonstrated that the model can capture key qualitative features of wetting-induced degradation, including stress generation and failure initiation. The model successfully reproduces the fundamental slaking behavior in which stress generation due to water migration leads to rock degradation. This represents an important first step toward clarifying slaking progression mechanisms and predicting long-term weathering rates and extents. Although this study focused on the behavior of a single rock particle, simulating slaking-induced compression in actual embankment structures by considering inter-particle contact forces could potentially contribute to the design and maintenance management of actual earth structures.

For the parameter set used in this analysis, a stress state reached the failure criterion at a certain depth below the rock surface after a certain time following immersion. In actual slaking tests, some rocks exhibit layered exfoliation over time similar to the analysis results, while others disintegrate into mud immediately after immersion. The model proposed in this study has the potential to reproduce various failure behaviors, and future work should investigate in detail which parameters influence the rated and mode of slaking. While this study focused on degradation during the wetting process, reproducing progressive rock degradation under repeated wetting-drying cycles is also a future challenge.

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