

Investigating the softening of weak interlayers during landslides using nanoindentation experiments and simulations

Jingjing Xu^a, Xuhai Tang^{a,*}, Zhengzhi Wang^a, Yufei Feng^{a,*}, Kang Bian^b

^a School of Civil Engineering, Wuhan University, Wuhan 430072, Hubei, China

^b State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Science, Wuhan 430072, Hubei, China

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ABSTRACT

Based on nanoindentation experiments and numerical simulations, an approach is developed to investigate the softening of weak interlayers, which might trigger landslides. The components of weak interlayers in natural slopes are mainly rock fragments and clay, which lead to the difficulty of preparing intact samples for traditional rock mechanical experiments. Additionally, most rock slopes are micro-sensitive fractured geological media. The slope failures are significantly influenced by the anisotropic and rheological mechanical evolution of weak interlayers, which is strongly related to their microstructure. In this work, the shale in weak interlayers is investigated using nanoindentation experiments, so the experimental samples can be very small and possess arbitrary shapes. The experimental results at the microscale are upscaled using the Gaussian mixture model and Mori-Tanaka scheme, which are then used in numerical modeling to investigate the failure of a slope in southwestern China. According to the results, after water immersion, the friction angle of shales is almost constant, while the elastic modulus and cohesion decrease significantly. The shear strength of weak interlayers decreases significantly so that the plastic zones develop along the weak interlayer, which leads to landslides.

1. Introduction

The instability of weak interlayers in a slope is the main reason for landslides in layered bedrock slopes. The erosion from rivers and rainfall often leads to a decrease in the strength of these weak interlayers, which may result in slope instability (Zhu, 2016). Since the beginning of the 20th century, many bedrock landslide disasters have been found to be related to the failure of weak interlayers, such as the Vaiont landslide in Italy (Müller, 1987) and the landslide near the Austin Dam in Texas (Wang, 1990). Approximately 90% of the 283 collapsed landslides in the Three Gorges Reservoir area in China were related to the instability of weak interlayers (Yin, 2004). Understanding and controlling the instability of weak interlayers are critical issues for assessing slope failure. Müller-Salzburg (1964) pointed out that a rapid rise in reservoir water levels is a major cause of landslides. In particular, karst caves and fissures are well developed at the trailing edge of landslides because of rainfall infiltration, which provides favorable conditions for the generation of bedding clay rocks in mountains. Fleming et al. (1989) found that the density of weak interlayers in slip zones is lower than that in overlying rock and soil. Haruo (2001) investigated five landslides in Japan and pointed out that landslide reactivation is mainly triggered by the increase in clay minerals. These

clay minerals are mainly montmorillonites, which are generated by the interaction between rocks and groundwater.

The softening of weak interlayers with water has been investigated intensively by macroscale experiments, including traditional uniaxial or triaxial compressive experiments. These experiments are applied to establish the relationship between saturation time and mechanical parameters, which include elasticity, compressive strength and cohesion (Anderson et al., 2010; Lin and Lai, 2013). However, macroscale experiments suffer from some limitations. First, the components of weak interlayers mainly consist of clay and rock fragments because of argillation or mylonitization. Therefore, it is difficult to prepare intact samples for macroscale experiments. Second, the anisotropic and rheological behaviors of weak interlayers are strongly related to their microstructure, including the percentages of chlorite, illite, kaolinite and muscovite (Lu et al., 2019).

The mineralogy and microstructure have a significant impact on the macroscale properties of rocks. The mineralogy and microstructure of rocks has been investigated by some researchers using advanced chemical detection devices (e.g., powder X-ray diffraction) (Luo et al., 2020) and image analysis devices (e.g., SEM) (Wang et al., 2020). As a sedimentary rock, shale is composed of a wide range of rock-forming minerals, including silicates, carbonates, organic materials and other

* Corresponding authors.

E-mail addresses: xuhaitang@whu.edu.cn (X. Tang), fengyf@whu.edu.cn (Y. Feng).

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constituents (Potter et al., 1980). The highly compacted micron-sized clay particles and nanometer-level microstructures in shale also have a significant impact on its mechanical macroscale property. The swelling of clay widely occurs when minerals interact with aqueous liquid due to the physicochemical process (Chenevert, 1970; Du et al., 2018). O'Brien and Chenevert (1973) classified clays into five main categories according to their relative hardness, hydrate tendency and disperse tendency. The interaction between shale minerals and water might lead to the softening of shale, which decreases its stiffness, hardness and strength (Anderson et al., 2010).

In addition to mineralogy and microstructure, the microscale mechanical properties of rocks also have a significant impact on their macroscale properties. The nanoindentation experiment provides a direct approach to estimate the microscale mechanical properties of the minerals in rocks and rock-like materials, including hardness, elastic modulus, plastic strain and fatigue strength (Oliver and Pharr, 1992; Oliver and Pharr, 2004; Shi et al., 2019). The nanoindentation test has the advantages of simple operation, high resolution, nondestruction and flexibility in preparing experimental samples. Additionally, it is easily combined with digital imaging technologies (e.g., atomic force microscopy, AFM). To investigate materials with multiphase composites, including cementitious materials (Constantinides et al., 2003), bone (Ulm et al., 2007) and steel (Jiri et al., 2010), grid indentation technology has been developed. This grid indentation technology provides an approach to investigate the multiscale properties of materials. Based on nanoindentation experiments, the properties of shale have been investigated by researchers, including the anisotropy (Bobko and Ulm, 2008), creep characterization (Vikas et al., 2012), softened zone (Lu et al., 2019) and homogenization elastic modulus (Liu et al., 2018).

In this paper, the instability of a slope with weak shale interlayers in southwestern China is investigated. Nanoindentation experiments are used to investigate the mechanical properties of microscale minerals in shale softened by immersion. After a large amount of data is obtained by the nanoindentation test, the Gaussian mixture model is applied to achieve the microscale mechanical property of each phase. Then, a homogenized analysis based on the Mori-Tanaka scheme is used to achieve the macroscale elastic property of shale. The microscale hardness values are achieved using special indenters, a Berkovich indenter and a cube-corner indenter, which are then used to determine the cohesion c and friction angle φ of the shale. Finally, these achieved experimental parameters are used in numerical models to analyze the slope failure caused by the softening of weak interlayers.

2. Multiscale analysis of shale with nanoindentation experiments and statistical model

2.1. Nanoindentation experiments

2.1.1. Investigating the elastic modulus and hardness at the nanoscale using nanoindentation

Nanoindentation is a technique that touches the material of interest with a diamond tip whose geometry and mechanical properties (e.g., elastic modulus and hardness) are known. The penetration depth and force are dynamically measured at resolutions of nanometers and micronewtons, respectively. The elastic modulus E and hardness H of shale samples can be analyzed from the generated force-displacement curve. Fig. 1 shows a typical loading-unloading curve and a schematic nanoindentation diagram. The origin of this curve is the point where the indenter first contacted the test surface. When the applied force increases, the displacement increases as well until the peak test force is achieved. The loading stage is the combination of elastic and plastic deformation. Then, the force is held for several seconds, followed by constant unloading, which can be regarded as the recovery of the pure elastic deformation.

For linear isotropic elastic materials, the initial unloading slope can be achieved by the elastic solution relating to the applied loading force

P and indentation depth h . The initial unloading slope is also called contact stiffness S (Oliver and Pharr, 1992).

$$S = \frac{dP}{dh} |_{h=h_{\max}} \quad (1)$$

where $h_{\max}$ is the maximum indentation depth.

The reduced modulus E_r is calculated as (Sneddon, 1965).

$$E_r = \frac{\sqrt{\pi}}{2\beta\sqrt{A_c}} S \quad (2)$$

where β is the dimensionless correction factor associated with the indenter tip shape and $\beta = 1.05$ is commonly used for the Berkovich indenter. A_c is the projected contact area of the indenter on sample surfaces, which is typically determined by a function of maximum contact depth, h_c : $A_c = f(h_c)$. For pyramidal, conical, and spherical indenters, the contact depth h_c is calculated as $h_c = h_{\max} - \epsilon \frac{P}{S}$ (ϵ is a constant that depends on the indenter tip and is set as 0.75 for the Berkovich indenter).

The relation between the reduced elastic modulus of the samples and indenter is expressed as.

$$E = (1 - \nu^2) \left[\frac{1}{E_r} - \frac{1 - \nu_i^2}{E_i} \right]^{-1} \quad (3)$$

where ν and ν_i are the Poisson's ratios of the sample and indenter, respectively. The Poisson's ratio of the sample can be reasonably assumed. The sensitivity analysis reveals that the uncertainty of 40% in Poisson's ratio only leads to an uncertainty of 5% in Young's modulus (Hay, 2009). For the diamond tip, the value of ν_i is 0.07 (Hay, 2009). Meanwhile, E_i and E are the Young's modulus values for the indenter and sample, respectively. The value of indenter E_i is 1140 GPa.

The hardness is calculated as.

$$H = \frac{P}{A_c} \quad (4)$$

2.1.2. Investigating cohesion and friction angle using the dual-indentation technique

The failure property of rock material can be described by the Mohr-Coulomb constitutive model: $\tau = \sigma_n \tan \varphi + c$. φ is the internal friction angle, and c is the cohesion. These two key mechanical parameters can be achieved by the dual indentation technique. The technique shows that hardness is primarily a function of the friction angle, cohesion and the apex angle (Ganneau et al., 2006).

In this work, the Berkovich indenter and cube-corner indenter are applied with the yield design theorems,

$$H = \frac{c}{\tan \varphi} \sum_{k=1}^6 (a_k \tan \varphi)^k \quad (5)$$

where a_k are fitting coefficients depending on the geometry of the indenters. The values of the fitting coefficients for the Berkovich indenter $a_k(\theta_B)$ and cube-corner indenter $a_k(\theta_{CC})$ are given in the literature (Ganneau et al., 2006).

Fig. 2 (a) displays the hardness ratio of the Berkovich and cube-corner indenters as a function of the friction angle in the interval $\varphi \in [5^\circ, 45^\circ]$; the hardness ratio increases almost linearly with the friction angle. Fig. 2 (b) shows the relation curve of the Berkovich indenter for the relation between H/c and the friction angle. Although this fitting function is strictly valid only within the interval $\varphi \in [5^\circ, 30^\circ]$, it is applicable to limited extrapolation to higher friction angles with small errors (Ganneau et al., 2006). This technique has been used in composite multiphase materials (e.g., cement) to estimate the influence of plastic properties on the mechanical behavior at the microscale (Palkovic et al., 2018).

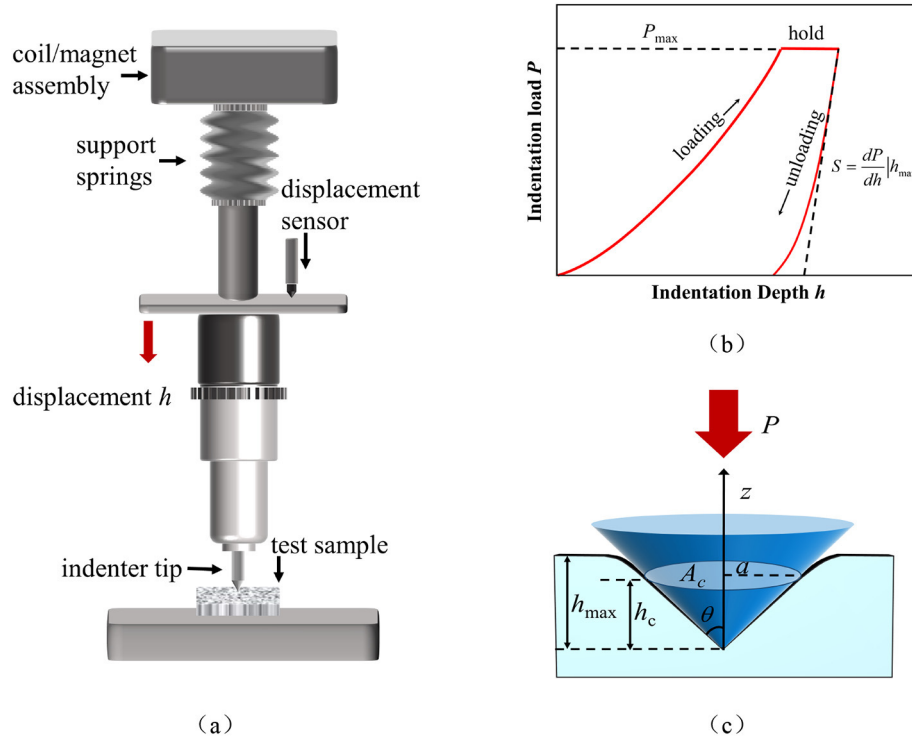


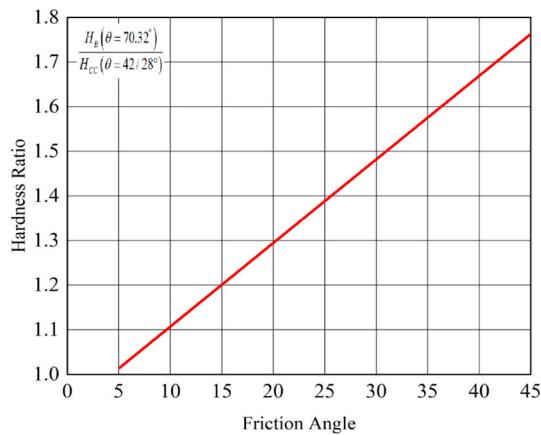
Fig. 1. Principle of indentation experiments.

2.2. Grid nanoindentation technique

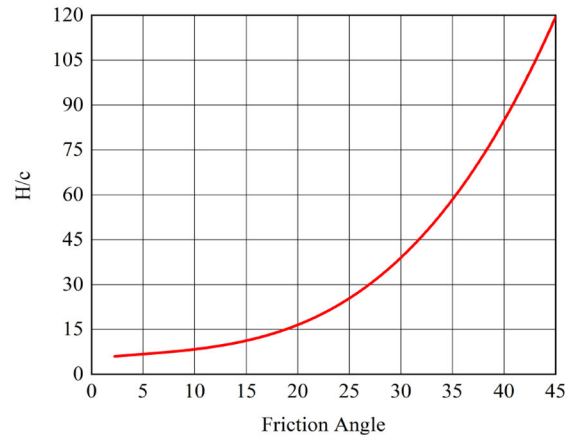
The grid nanoindentation technique is widely used to deal with complex composite materials and overcome the following difficulties in nanoindentation tests (Randall et al., 2009). First, it is difficult to repeat an indent on a specific material phase. Second, geomaterials are difficult to polish because of the significant mismatch among different constituent phases. The resultant high surface roughness variations cause large statistical deviations in the indentation results. The grid indentation technique statistically provides both quantitative and qualitative information about the morphology and mechanical properties of each phase (Constantinides et al., 2006).

In the grid nanoindentation technique, the indentation length scale

is a key parameter used to avoid interaction between two individual phases in the microstructure. The setting of indentation depth h , grid size l , and the number of indenters N are determined in this work according to the following conditions: (1) The grid size l should be much larger than the indentation depth h , which satisfies the statistical independence. (2) The N indenters should be applied over an area that is much larger than the length scale of the individual material phases, D , to avoid sampling effects $D < l\sqrt{N}$ (Bobko and Ulm, 2008). (3) The indentation depth h should be shallow enough to ensure that the criterion $h/D < 0.1$, which ensures that the difference between the elastic property of the indented composite and the elastic property of a single phase is smaller than 10% (Randall et al., 2009). (4) The indentation depth h is three times larger than the surface roughness R_q , $h > 3R_q$,



(a) The linear relation between hardness ratio and friction angle



(b) The relation curve of Berkovich indenter, for the relation between H/c and friction angle

Fig. 2. The relation curves of dual-indentation technique.

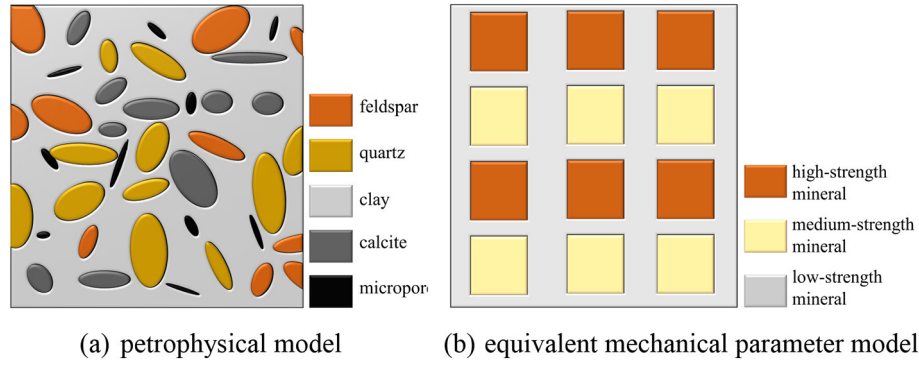


Fig. 3. Transformation of petrophysical model into equivalent mechanical parameter model.

which satisfies the assumption of a perfectly flat infinite half space (Bobko and Ulm, 2008).

2.3. Upscaling analysis

The statistical analysis of experimental results, achieved by the grid nanoindentation technique, provides an approach to generate the relation between macroscale and microscale mechanical properties. The Gaussian mixture model (GMM) is used to represent the probability distribution of microscopic phases. The Mori-Tanaka (M-T) method is used to obtain the equivalent mechanical parameters from the nanoscale to the centimeter scale according to the volume fraction of different minerals and the component mechanics model.

2.3.1. Gaussian mixture model

The Gaussian mixture model assumes that the data obey the Gaussian mixture distribution, that is, the data can be regarded as generated from k Gaussian distributions.

The probability distribution of the Gaussian mixture model is

$$P(x|\theta) = \sum_{k=1}^K \alpha_k \phi(x|\theta_k) \quad (6)$$

where α_k is the probability that the data belong to the k -th component, which satisfies $\alpha_k \geq 0$, $\sum_{k=1}^K \alpha_k = 1$.

$\phi(x|\theta_k)$ is the Gaussian distribution density function of the k -th component and $\theta_k = (\mu_k, \sigma_k^2)$.

$$\phi(x|\theta_k) = \frac{1}{\sqrt{2\pi}\sigma_k} \exp\left(-\frac{(x-\mu_k)^2}{2\sigma_k^2}\right) \quad (7)$$

where μ_k is the expected value and σ_k^2 is the standard deviation.

The maximum likelihood method is used to determine the expected value μ_k , standard deviation σ_k^2 , and probability α_k . For the Gaussian mixture model, the log-likelihood function is

$$\log P(x, \gamma|\theta) = \sum_{k=1}^K n_k \log \alpha_k + \sum_{j=1}^N \gamma_{jk} \left[\log\left(\frac{1}{\sqrt{2\pi}}\right) - \log \sigma_k - \frac{1}{2\sigma_k^2}(x_j - \mu_k)^2 \right] \quad (8)$$

Since the above equation cannot take the derivative directly, the EM algorithm proposed by Dempster and Laird (1977) is applied for iterative solution. Each iteration consists of two steps, the E step and the M step, which repeat until convergence.

(1) E step: calculate the possibility $\hat{\gamma}_{jk}$ that each data x_j comes from the k -th component.

$$\hat{\gamma}_{jk} = \frac{\alpha_k \phi(x_j|\theta_k)}{\sum_{k=1}^K \alpha_k \phi(x_j|\theta_k)}, j = 1, 2, \dots, N; k = 1, 2, \dots, K \quad (9)$$

(2) M step: Find the maximum value and calculate the model parameters of the new iteration.

$$\hat{\mu}_k = \frac{\sum_{j=1}^N \hat{\gamma}_{jk} x_j}{\sum_{j=1}^N \hat{\gamma}_{jk}}, k = 1, 2, \dots, K \quad (10)$$

$$\hat{\sigma}_k^2 = \frac{\sum_{j=1}^N \hat{\gamma}_{jk} (x_j - \mu_k)^2}{\sum_{j=1}^N \hat{\gamma}_{jk}}, k = 1, 2, \dots, K \quad (11)$$

$$\hat{\alpha}_k = \frac{\sum_{j=1}^N \hat{\gamma}_{jk}}{N}, k = 1, 2, \dots, K \quad (12)$$

2.3.2. Mori-Tanaka method

The Mori-Tanaka method is widely used for the homogenization of multiphase elastic composites. The Mori-Tanaka method approximates the interaction among the different phases by assuming that each inclusion is embedded (Liu et al., 2018). As shown in Fig. 3, although the variety of mechanical properties is obvious among different minerals in geomaterials, we can divide them into three categories according to the strength at the microscale: high-strength minerals, medium-strength minerals and low-strength minerals. These three categories constitute a three-phase medium mechanical model, which can be regarded as isotropic at the nanoscale (Shi et al., 2019).

The equivalent volume modulus K_M and shear modulus G_M of each phase are calculated using the following equations (Mori and Tanaka, 1973):

$$K_M = \frac{\sum f_r \frac{k_r}{3k_r + 4\mu_{low}}}{\sum \frac{f_r}{3k_r + 4\mu_{low}}} \quad (r = 0, 1, 2) \quad (13)$$

$$G_M = \frac{\sum \frac{f_r \mu_r}{\mu_{low}(9k_{low} + 8\mu_{low}) + 6\mu_r(k_{low} + 2\mu_{low})}}{\sum \frac{f_r}{\mu_{low}(9k_{low} + 8\mu_{low}) + 6\mu_r(k_{low} + 2\mu_{low})}} \quad (14)$$

$$k_r = \frac{E_r}{3(1 - 2\nu_r)} \quad (15)$$

$$\mu_r = \frac{E_r}{2(1 + 2\nu_r)} \quad (16)$$

where k_r is the mineral particle volume modulus. μ_r is the mineral particle shear modulus. f_r is the volume fraction of different phases. ν_r is the Poisson's ratio of different phases. E_r is the elastic modulus of different phases. $r = 0$ represents high-strength minerals, $r = 1$ represents medium-strength minerals, and $r = 2$ represents low-strength minerals.

Recognizing the influence of micropores in low-strength minerals, the equivalent volume modulus k_{low} and the equivalent shear modulus μ_{low} of low-strength minerals are calculated as follows. μ_s and k_s are the shear modulus and volume modulus of low-strength minerals. The porosity ϕ of shale is 3.5% in this paper.

$$k_{\text{low}} = \frac{4(1 - \phi)k_s\mu_s}{4\mu_s + 3\phi k_s} \quad (17)$$

$$\mu_{\text{low}} = \frac{(1 - \phi)\mu_s}{1 + 6\phi \frac{k_s + 2\mu_s}{9k_s + 8\mu_s}} \quad (18)$$

After obtaining the equivalent mechanical parameters of the three-phase medium model, the homogenization elastic modulus E_{hom} can be calculated by the following equation:

$$E_{\text{hom}} = \frac{9K_M G_M}{3K_M + G_M} \quad (19)$$

3. Experimental procedure and results of nanoindentation experiments

3.1. Experimental sample preparation

The present experimental samples are taken from the Silurian Longmaxi Formation shale, which is blue-gray and intermediary weathered. It has the characteristics of lamellation structure and joint fissure development. The shale samples exhibit argillaceous cementation with poor bonding among structural planes. The same shale samples were also investigated by Bian et al. (2019), who measured the main mineral components of these shale samples using traditional uniaxial compression tests and D8 Advance X-ray diffraction. The main mineral components of these shale samples are chlorite, muscovite, quartz, feldspar and a small amount of calcite, as shown in Table 1. The microstructure analysis results show that the oriented arrangement of chlorite and muscovite constitutes the bedding plane of shale. Quartz, feldspar and calcite are mainly distributed in the shale pores but less near the bedding plane. The pore-filling cements between minerals are mainly chlorite, quartz and feldspar (Bian et al., 2019).

3.2. Experimental procedure

As shown in Fig. 4, the size and geometry of the present shale samples can be arbitrary. The samples are prepared as follows: first, irregular shale rocks are processed into 2 cm high experimental samples, whose top surface and bottom surface are paralleled and polished (see Fig. 4); second, the samples are placed in a 45 °C environment and dried for 24 h; third, a BUEHLER polishing instrument is used to polish the samples with sandpapers of different grain fineness levels of P800, P1200, P2500, and P5000; finally, the experimental samples are further polished to reduce surface roughness as much as possible using an extra fine alumina suspension, which consists of 0.3 μm alumina powder and a mixture of ethanol and ethylene glycol at a 1:1 volumetric ratio. During the whole polishing process, ethanol is used to clean the samples to avoid the potential hydration effect and ensure that the sample surface is clean, flat, and smooth. The sample surface roughness in this

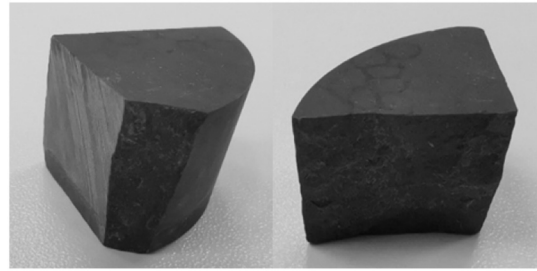


Fig. 4. Shale samples with arbitrary size and geometry, which can be easily obtained from the fragmented weak interlayers of slopes.

work can reach approximately 60 nm, which is measured using the AFM test.

The three samples are immersed in water for different immersion times t . These samples are tested using the nanoindentation experiment with the Berkovich indenter and cube-corner indenter when the immersion time t is 0 days, 1 day, 3 days, 5 days and 10 days. The indentation grid of the Berkovich indenter consists of 225 indentations, which is a 15 × 15 square grid. The space between two adjacent indentations is 20 μm to avoid interactions among adjacent indentations. The indentation grid of the cube-corner indenter consists of 100 indentations, which is a 10 × 10 square grid. The space between two adjacent indentations is 30 μm. The REA (representative elementary area) of shale is found to be 250 μm × 250 μm based on the box-counting method (Liu et al., 2018) and porosity indicator (Liu and Ostadhassan, 2017). The nanoindentation area is 300 μm × 300 μm, which is larger than the REA; therefore, the fraction of mineral composition becomes constant at this scale. The penetration depth satisfies the scale separation criterion and the assumption of a continuum indentation model of an infinite half-space, which allows the local measurement of material properties. The same loading rate and loading force are set for these two different indenters. For each indentation, the experimental procedure includes loading at a rate of 0.8 mN/s up to a maximum load of 4 mN, a holding period of 2 s, and unloading at a rate of 0.8 mN/s.

3.3. Experimental results and discussion

A large number of indentations at different locations provide statistical data for analyzing the mechanical properties of the samples. The data from a total of 3 samples were combined to reduce the heterogeneity of different samples. The inaccuracies in nanoindentation tests frequently appear due to porosities in the material, surface roughness and material failure. These inaccuracies can be reduced by removing the unreasonable data from 675 indenter results according to the load-displacement curve. A Gaussian mixture model is used to identify mineralogical phases based on their mechanical property distribution, including indentation modulus E and indentation hardness H . Three mineral components are clustered, which can be presented by ellipses with different principal axes, as shown in Fig. 5 (a)(c)(e)(g)(i). The expected values of Gaussian distributions of shale samples under different immersion times t are illustrated in Table 2. As shown in Fig. 5 (b, d, f, h, j), to demonstrate for better display, the experimental frequency plots of the elastic modulus are fitted by probability density functions (PDF), which correspond to the GMM.

The Mori-Tanaka method is applied to evaluate the mechanical properties at the macroscale level based on the clustering results of the grid nanoindentation test with the Gaussian mixture model. In a previous study (Liu et al., 2018), it was found with the Mori-Tanaka method that the elastic properties achieved by nanoindentation experiments are close to those obtained by macroscale experiments. The three components of the Gaussian mixture model correspond to low-strength, medium-strength, and high-strength minerals. It is known that

Table 1
Composition analysis of shale samples (Bian et al., 2019).

Sample number	Mineral content (%)				
	chlorite	muscovite	quartz	feldspar	calcite
1	33.56	17.03	31.25	12.36	5.80
2	41.78	23.75	21.67	12.06	0.74
3	39.02	22.04	20.37	14.93	3.63

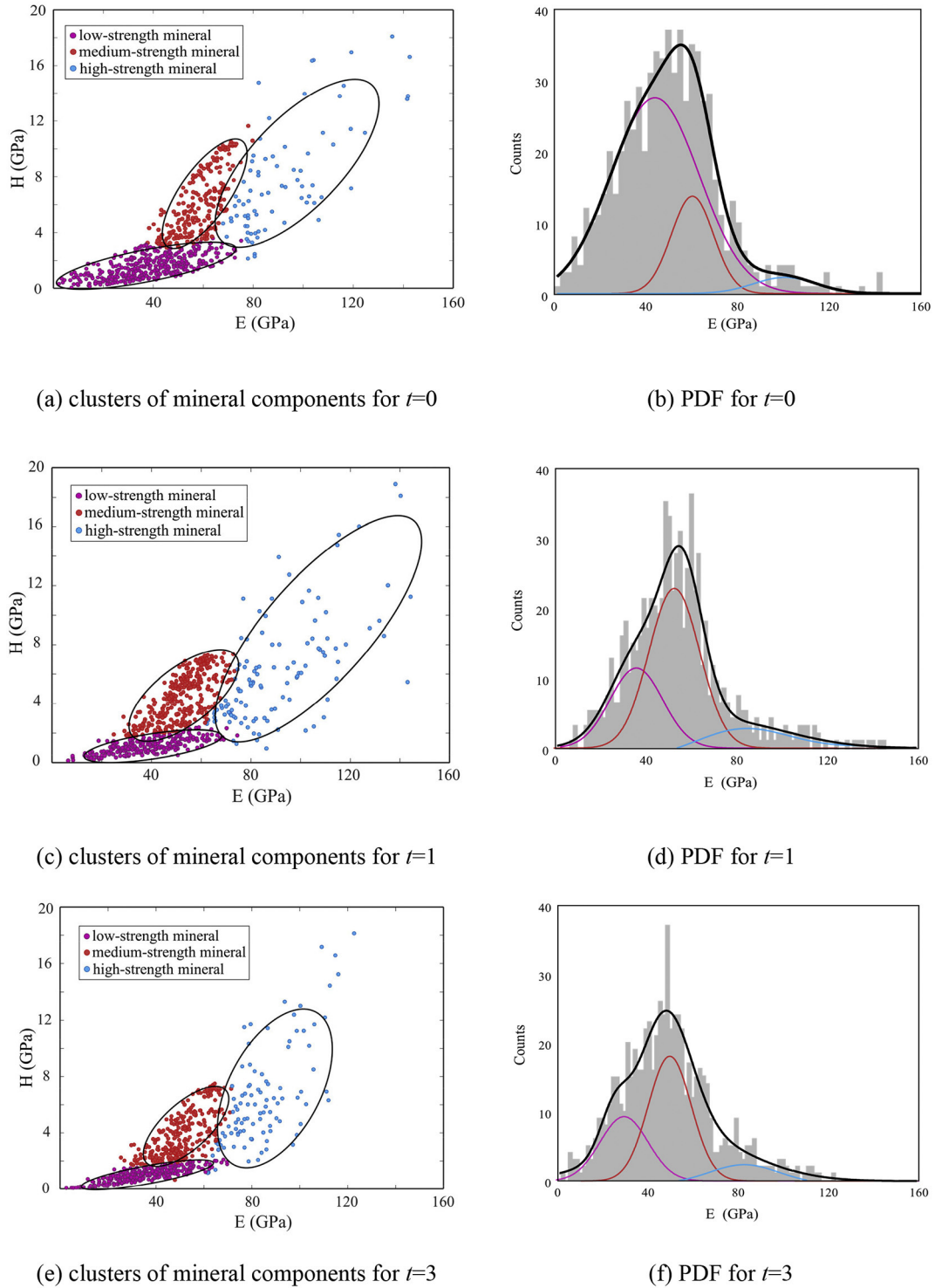


Fig. 5. Analyzing indentation hardness and elastic modulus of shale using nanoindentation results for different water immersion times t .

low-strength minerals dominated by clay minerals are the base in shale, while medium-strength and high-strength minerals are embedded minerals, including muscovite, feldspar and quartz.

The surface fraction of each phase, obtained by GMM analysis, and the volume fraction are identical in perfectly disordered material (Delesse, 1847). The data in Table 2 are substituted into formulas (13)–(19) to calculate the homogenization elastic modulus E_{hom} . The results are plotted as the relation curve between the homogenization elastic modulus E_{hom} and the immersion time, as shown in Fig. 7 (a).

The relation of hardness H to the cohesion c , internal friction angle

φ and half apex angle θ of the indenter can be achieved using the dual indentation technique. In shale, only the clay mineral exhibits cohesive-frictional behavior, which dominates the overall plastic property of shale. The inclusion phases embedded in clay are assumed to be elastic and do not experience plasticity (Palkovic et al., 2018). Thus, we can calculate the cohesion c and internal friction angle φ of shale based only on the indentation hardness H of the low-strength clay mineral. As shown in Table 3, the hardness H of low-strength minerals under different immersion times t is determined by GMM when the Berkovich indenter is applied. PDF deconvolution technology is directly used to fit

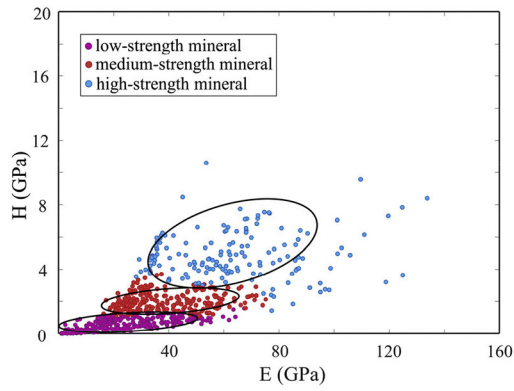
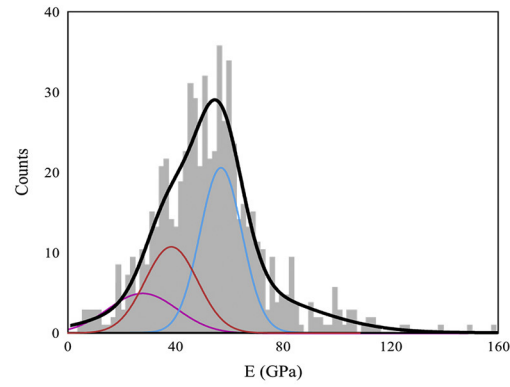
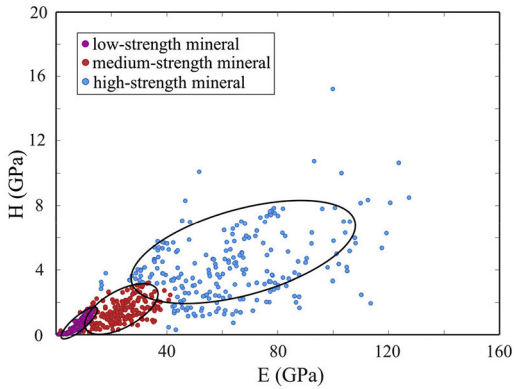
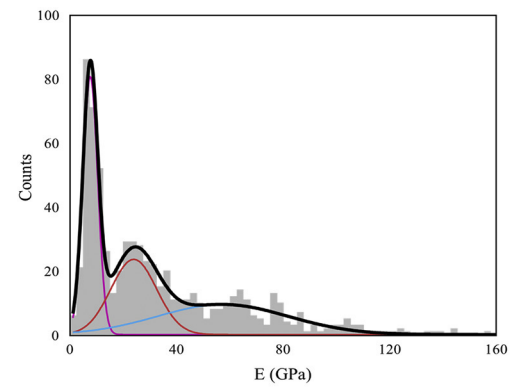
(g) clusters of mineral components for $t=5$ (h) PDF for $t=5$ (i) clusters of mineral components for $t=10$ (j) PDF for $t=10$

Fig. 5. (continued)

Table 2

Comparison of the mechanical properties of different mineral phases after immersion treatment.

Immersion time t	Mineral	E (GPa)	Standard error	H (GPa)	Probability	E_{hom} (GPa)
0 day	Low	38.8	7.6	1.65	0.55	43.097
	Medium	58.0	1.4	5.81	0.34	
	High	89.1	19.2	7.85	0.11	
1 day	Low	38.9	11.3	1.08	0.32	46.044
	Medium	53.1	3.2	4.28	0.53	
	High	90.3	20.4	6.22	0.15	
3 day	Low	34.9	12.4	0.95	0.39	41.674
	Medium	51.4	1.5	3.71	0.49	
	High	90.3	18.1	6.78	0.12	
5 day	Low	20.5	21.7	0.86	0.32	33.712
	Medium	36.5	9.7	1.75	0.33	
	High	68.7	4.9	4.89	0.35	
10 day	Low	7.9	0.1	0.59	0.34	23.429
	Medium	24.2	0.8	1.59	0.31	
	High	64.5	7.3	4.34	0.36	

Table 3

The strength parameters of shale after immersion treatment.

Immersion time t	H (GPa)	H_c (GPa)	Hardness ratio	Cohesion c (MPa)
0 day	1.65	0.97	1.701	16.65
1 day	1.08	0.65	1.662	10.90
3 day	0.95	0.55	1.730	9.59
5 day	0.86	0.53	1.654	8.68
10 day	0.59	0.33	1.735	5.96

the peaks of the frequency plots of the distribution function when the cube-corner indenter is applied. Fig. 6 shows the typical PDF-based deconvolution results for immersion time t . The mean value of peaks represents the mean phase property. The hardness H_c of the low-strength mineral measured by the cube-corner indenter is the lowest strength peak. During water immersion, the hardness ratios of low-strength minerals are stable at approximately 1.7 (Table 3). The internal friction angle φ can be calculated using Fig. 2 (a) according to the hardness ratios. The internal friction angle φ only fluctuates slightly with the immersion time (see Fig. 6 (f)), and its mean value is 42.5° . For a given hardness H and internal friction angle φ , the cohesion c can be calculated using Eq. (5) and Fig. 2 (b). Cohesion c decreases rapidly with the hardness of shale (see Fig. 7(b)). The internal friction angle φ and cohesion c measured by the micro experiment agree well with that of the macro triaxial compression test (Bian et al., 2020).

According to Figure 5, 6 and 7, Tables 2 and 3, the features of mechanical property evolution with immersion time can be revealed:

First, the homogenization elastic modulus E_{hom} of shale exhibits a significant reduction after water immersion. However, the homogenization elastic modulus increases slightly after 1 day of immersion. Overall, the homogenization elastic modulus decreases significantly when the immersion time t is more than 3 days. The present results agree with the macro experimental results in Bian et al. (2019). The downward trend is flattened after 10 days of immersion and approximately obeys a log-normal distribution, which can be observed in previous macro experiments (Bian et al., 2019).

Second, the elastic moduli of the three clusters of minerals all decrease with the water immersion time. For low-strength minerals, the elastic modulus starts to decrease rapidly after one day of immersion. For medium-strength minerals and high-strength minerals, the elastic modulus starts to decrease rapidly after five days of immersion. The

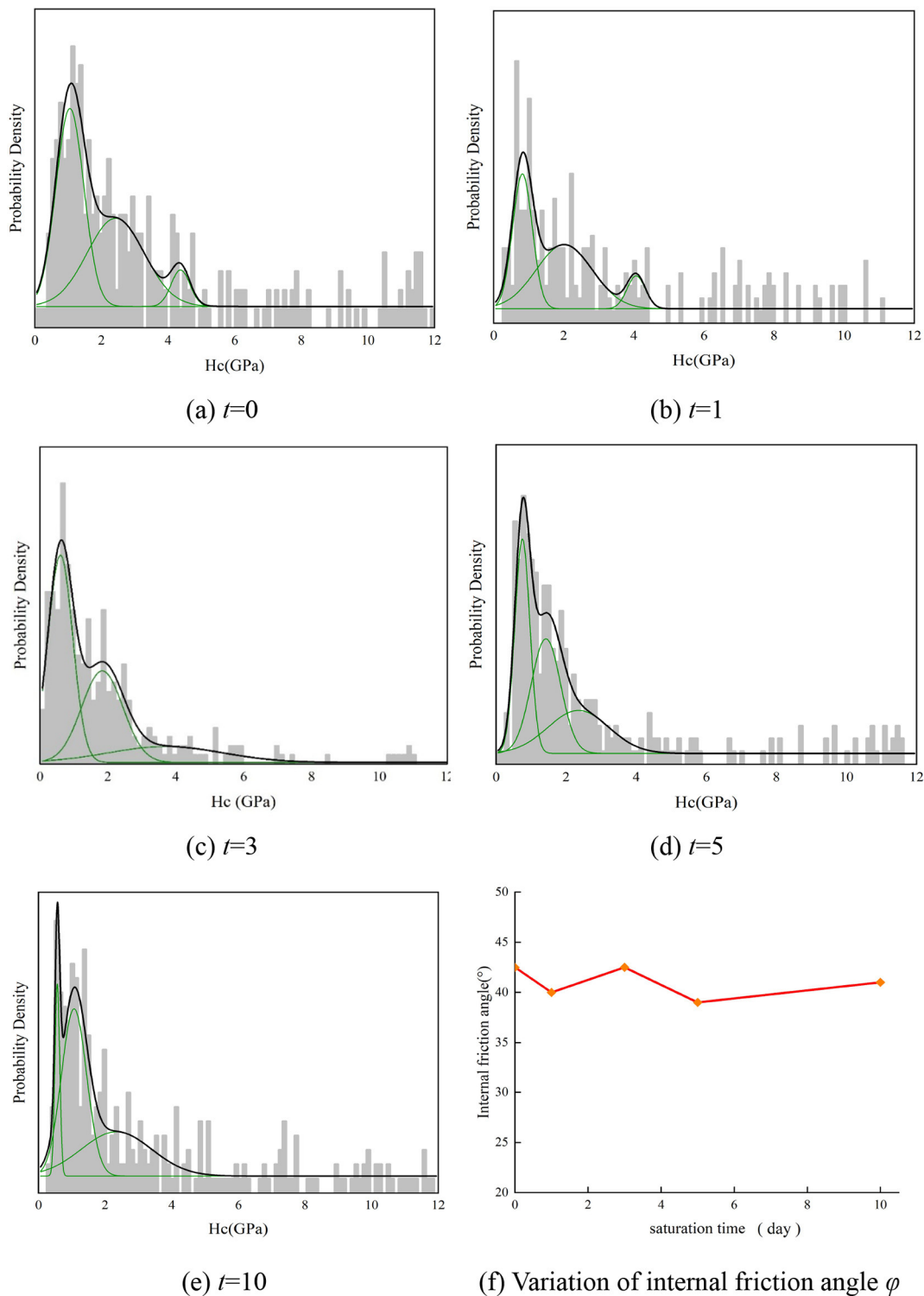


Fig. 6. The data characterized by PDF deconvolution method for different immersion times t .

difference is because the main component of low-strength minerals is chlorite, which is more sensitive to water.

Third, the change trends of the volume fraction with the water immersion time are different for the three clusters of minerals. The volume fraction of low-strength minerals decreases with the water immersion time. The volume fraction of medium-strength minerals experiences increases during the first day of water immersion, which then decreases with the water immersion time. The volume fraction of high-strength minerals increases after five days of water immersion.

The interlaminar expansion force of mineral crystals increases by approximately 111.8% (Anderson et al., 2010; Zhu et al., 2015). The low-strength minerals are mainly chlorite, which has significant hydro-expansiveness. With the adsorption of water molecules, a nonuniform expansion stress is generated, which leads to the failure of chlorite. The absence of low-strength minerals provides substantial surface area and pore space for enhancing water penetration, which further destroys the medium-strength minerals.

Finally, for low-strength minerals, the cohesion c and hardness H

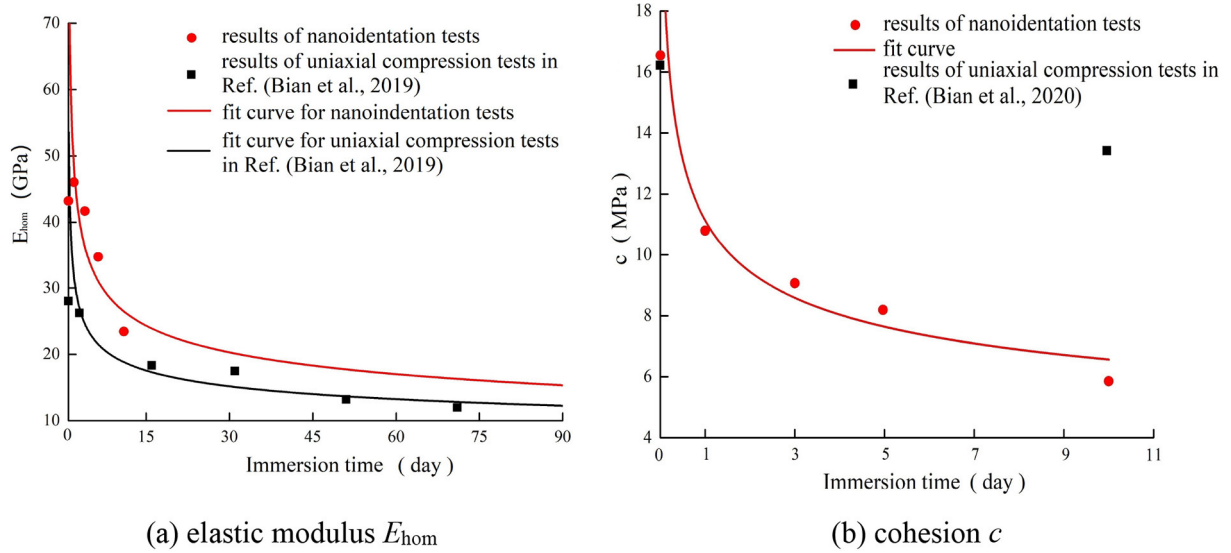


Fig. 7. Variation of mechanical properties with immersion time.

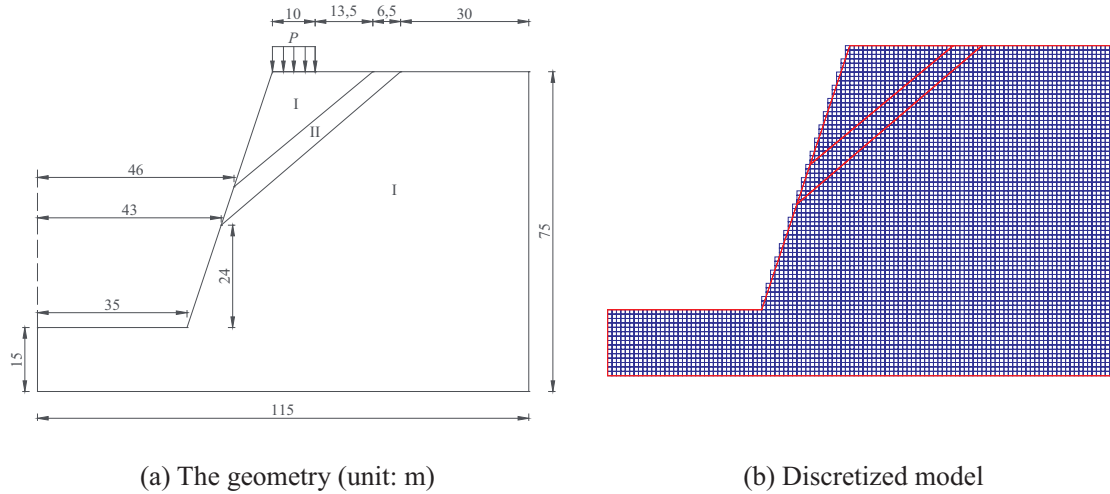


Fig. 8. The rock slope with a weak layer.

both decrease with immersion time. This phenomenon is due to the dissolution of chlorite by water. The contact among mineral particles becomes smooth, and the cementation ability is weakened, resulting in the reduction of cohesion. In Fig. 7 (b), without immersion, the present c measured by nanoindentation tests agrees with the results of traditional triaxial tests. After immersion for several days, the results of nanoindentation tests and the results of traditional triaxial tests are very different. The reason may be that the ratio of rock-water interactions (the surface of samples) to the volume of samples is much different for the two types of experiments.

4. Numerical simulation of slope failure caused by water immersion

The experimental parameters achieved in Section 3 are used to analyze the slope failure caused by the softening of weak interlayers, with numerical modeling based on the numerical manifold method (Yang et al., 2016; Yang et al., 2018).

4.1. Failure criteria

Based on the Mohr-Coulomb criterion, an ideal elastic-plastic model

is used to evaluate the yield condition of a slope model.

$$(1 + \sin \varphi) \sigma_1 - (1 - \sin \varphi) \sigma_3 - 2c \cos \varphi = 0 \quad (20)$$

where σ_1 , σ_2 and σ_3 are the first, second and third principle stresses, respectively, which satisfy the following condition:

$$\sigma_1 > \sigma_2 > \sigma_3 \quad (21)$$

Here, a criterion based on the evolution of plastic zones is applied (Yang et al., 2020). The cohesion and internal friction angle of weak interlayers decrease during the slope failure process. The plastic zones of the slope are obtained by solving the elastic-plastic problem, which extends from the slope top to the slope toe along the weak interlayer, which leads to slope failure at this instant (Yang et al., 2019a; Yang et al., 2019b).

4.2. Numerical models

The geometry of a slope is plotted in Fig. 8 (a). The fixed constraint is applied on the bottom boundary of this slope, while the normal constraint is employed on the left side and right side of this slope. A load of 100 MPa is applied to the top of the slope. The discretized model of this example has 6086 manifold elements and 6417 nodes (Fig. 8

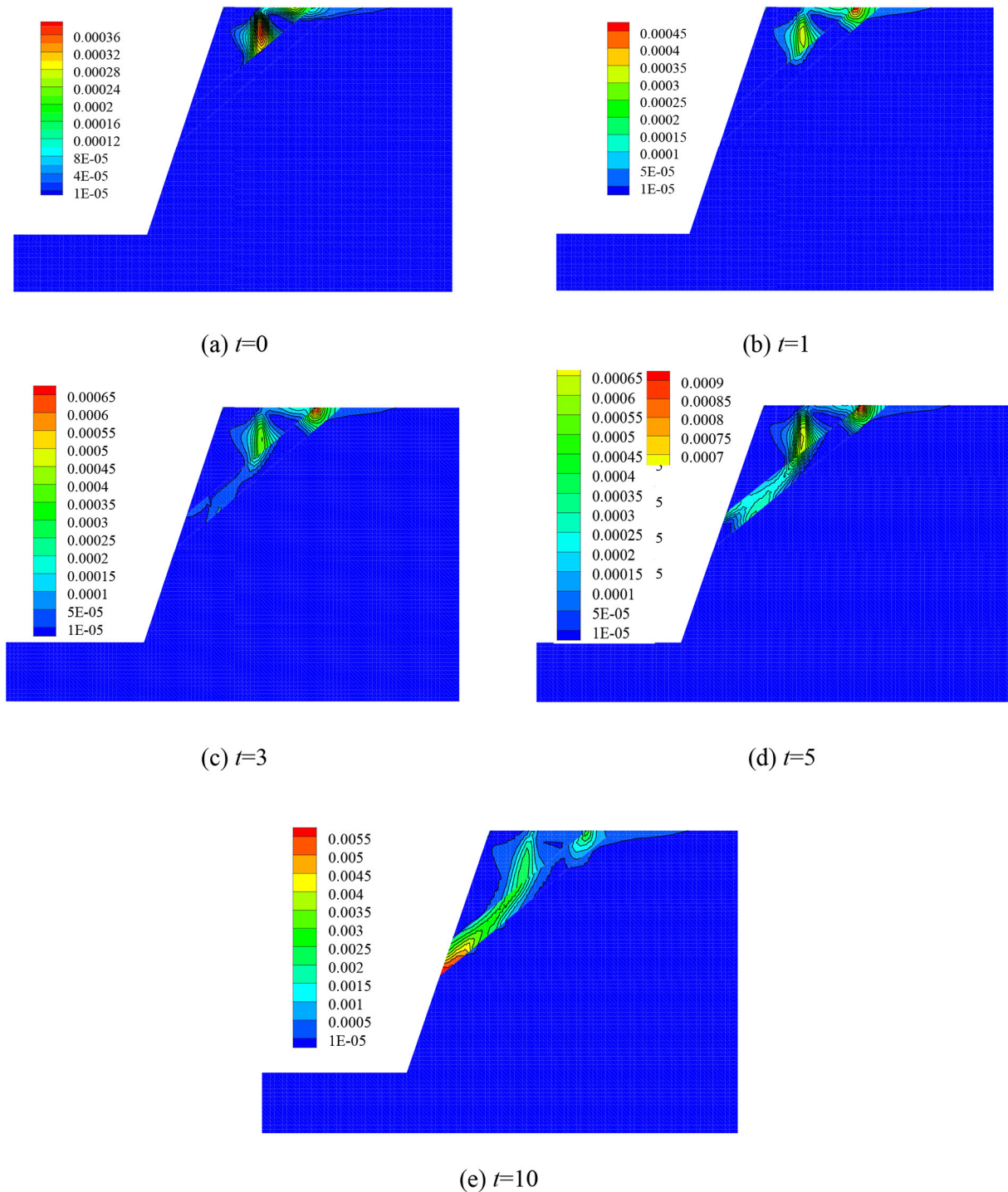


Fig. 9. Equivalent plastic strain contours of the slope at different immersion times t .

(b)).

The bedrock I of the slope is Maokou Formation limestone with a density of 2710 kg/m^3 , a Poisson's ratio of 0.2, an internal friction angle of 45° , a cohesion of 17.3 MPa and an elastic modulus of 82 GPa. The weak interlayer II in the mountain is mainly carbonaceous shale, which is deposited by argillaceous debris transported by weathering. The density of the weak interlayer is 1750 kg/m^3 , the Poisson's ratio is 0.36 and the internal friction angle is 42.5° . Under long-term geological evolution tectonic action, rocks are often fragmented along weak interlayers, which leads to relatively higher permeability and enhances the influence of water infiltration. In this work, the decrease in elastic

modulus and cohesion in the weak interlayer are determined by the above nanoindentation test (see Fig. 7).

4.3. Numerical simulation results

The simulation results reflect the slope failure process influenced by weak interlayer softening. The equivalent plastic strain contours of the slope corresponding to different immersion times t are plotted in Fig. 9. Water-rock interaction occurs, so the integrity and compactness of the weak interlayer are gradually destroyed, and the long-term shear strength parameters are continuously reduced. Fig. 9 demonstrates that

when the strength of the weak interlayer decreases, plastic zones appear in the vicinity of the weak interlayer. When the immersion time is 10 days, the plastic strain zones have developed from the slope top to the slope toe, which leads to the failure of the slope. The landslide and bedrock relatively slipped, causing overall instability and destruction.

5. Conclusion and discussion

In this work, the microscale and macroscale properties of shale in weak interlayers are investigated using nanoindentation experiments. The experimental results are then used in numerical modeling to investigate the failure of a slope in southwestern China. The contributions of the present work include the following:

First, a procedure is developed to investigate the slope failure using nanoindentation experiments and numerical simulations. The components of weak interlayers in natural slopes are mainly rock fragments and clay, which leads to the difficulty of preparing intact samples for traditional rock mechanical experiments. With the nanoindentation experiments, the experimental samples can be small and possess arbitrary shapes.

Second, according to the nanoindentation experimental results, the elastic modulus E_{hom} decreases with increasing water immersion time. The measurement results of hardness, based on the dual indentation technique, reveal that the internal friction angle ϕ is almost unchanged, and the cohesion c decreases significantly with increasing water immersion time. The results of the nanoindentation test agree with the results of the traditional uniaxial compression test (Bian et al., 2019).

Third, this work provides an approach to understand the mechanism of slope failure at the microscale. The statistical analysis of the Gaussian mixture model shows that the softening of shale is mainly due to the collapse of clay minerals. Chlorite, which accounts for the main component of clay minerals in shale, is softened or dissolved. The disintegration and dispersive stripping of low-strength minerals produce a loose and porous floc structure. The strength and volume fraction of the medium-strength mineral decrease because of further water erosion, which penetrates into the interior along pores and fissures.

Last, the material property in the numerical manifold method simulation is determined by the nanoindentation test. The numerical results show that when the shear strength of the weak interlayer decreases, the equivalent plastic strain zones extend, which leads to overall slope failure.

In this work, the influence of clay swelling at the macroscale is ignored in the simulation, even though it is considered at the microscale by nanoindentation tests. The present method is potentially useful for analyzing the failure of rock slopes. The influence of clay swelling at the macroscale will be studied in future work.

Data availability

Datasets related to this article can be found at <https://data.mendeley.com/datasets/zh9f759gb9/draft?a=8d6450ac-6639-4286-a0e9-6f51c67a558b>, an open-source online data repository hosted at Mendeley Data.

Declaration of Competing Interest

None.

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