FIB-SEM Analysis of Slip Surface Clay

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Abstract

This study obtains the characteristic clay mineral types, their relative contents, mineral particle sizes, and porosity of the slip surface and adjacent surfaces through in-situ analytical calculations. The experiment reveals the spatial distribution characteristics and differences in mineral composition and structure between the slip surface and adjacent surfaces using clear and reliable physical images and test data, thereby elucidating the physical pathways and mechanisms of soil slope failure and slip surface strength reduction. The experiment utilizes fresh slip zone soil without subsequent weathering, employing the AMICSCAN mineral analysis electron microscope system, which integrates a high-resolution field emission scanning electron microscope, the latest generation (third generation) automatic mineral identification and characterization software AMICS (Automatic Mineral Identification and Characterization System, with resolution up to 0.5 m pixel), and ultra-large-area high-resolution imaging software into a unified mineral and structural analysis system. Based on the uniqueness of mineral atomic proportions, it identifies mineral types and their distribution. Furthermore, using the Helios NanoLab-650 focused ion beam scanning electron microscope (FIB-SEM) from FEI Company combined with an X-ray energy dispersive spectrometer (EDS), the high-resolution backscattered electron two-dimensional images from the electron microscope are integrated with the characteristic spectra measured by the spectrometer. With the aid of Avizo Fire software, based on point and line elemental scanning images from the EDS and 500 frames of focused ion beam scanning electron microscope images obtained by scanning at one-micron intervals, the three-dimensional distribution of pore space in the slip zone soil is visually reconstructed and calculated. Through approximate conversion from volume ratio to content ratio, this provides authentic, accurate, and reliable evidence for revealing the formation pathways and mechanisms of the slip surface. The experiments reveal: 1) At the micron scale, a clear boundary is visible between the slip surface and adjacent surfaces, with non-uniform thickness of the slip surface. On backscattered images at 10-nanometer resolution, the slip surface structure is dense with small pores that are difficult to resolve; 2) In a three-dimensional slip zone soil sample scanned and sectioned into a cube measuring 17 micrometers in width and 19 micrometers in height, the porosity of the slip surface portion is 0.0331, while that of the adjacent surface portion is 0.0754, with the porosity of the adjacent surface being approximately 2.3 times that of the slip surface; 3) The characteristic spectral images and data from the energy dispersive spectrometer show that characteristic elements of montmorillonite—Na, Ca, and Mg—exhibit prominent peaks on the slip surface, with a precipitous drop near the boundary line, proving that montmorillonite is enriched on the slip surface, while no montmorillonite is detected on the adjacent surface; 4) The characteristic element K of illite on the adjacent surface is higher than that on the slip surface, indicating that the illite content on the adjacent surface is significantly higher than on the slip surface. The experiment confirms using clear physical images and accurate spectral data that significant differences exist in mineral composition and structure between the slip surface and adjacent surfaces, and the low porosity of the slip surface may be caused by the overlying soil pressure on the slip surface. This study is the first to reveal the spatial differences in mineral composition, porosity, crystallinity, and particle size between the slip surface and adjacent surfaces using an in-situ experimental method, providing reliable evidence for elucidating the evolution pathways of slip surfaces. To ultimately establish a cross-scale evolution model for slip surfaces and soil masses, we need to conduct more comparative analyses of compositional and structural differences, macroscopic strength, and micro-nano scale structures between slip surfaces and adjacent surfaces, as well as analyses of mineral evolution kinetic processes.

Full Text

FIB-SEM Analysis of Clay in Sliding Surface

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Abstract

Through in situ analysis and calculation, this study obtained the characteristic clay mineral types, relative contents, mineral particle sizes, and porosity of sliding surfaces and adjacent surfaces. The experiment reveals the spatial distribution characteristics and differences in mineral composition and structure between sliding surfaces and adjacent surfaces through clear and reliable physical images and test data, thereby elucidating the physical pathways and mechanisms of soil slope failure and sliding surface strength reduction. The study employed fresh, non-weathered slip zone soil and utilized the AMICSCAN mineral analysis electron microscope system, which integrates high-resolution field emission scanning electron microscopy, the latest generation (third generation) automatic mineral analysis software AMICS (Automatic Mineral Identification and Characterization System, with resolution up to 0.5 m per pixel), and ultra-large-area high-resolution imaging software. Based on the uniqueness of mineral atomic ratios, the system identifies mineral types and their distribution. Furthermore, using FEI’ s Helios NanoLab-650 focused ion beam scanning electron microscopy (FIB-SEM) combined with X-ray energy dispersive spectroscopy (EDS), high-resolution backscattered electron two-dimensional images from the electron microscope were combined with characteristic spectra measured by the spectrometer. With the aid of Avizo Fire software, point and line elemental scanning images from the energy spectrum were combined with 500 frames of focused electron beam scanning electron microscopy images obtained at one-micron intervals to visually reconstruct and calculate the three-dimensional spatial distribution of pore space in slip zone soil. Volume ratios were approximated and converted to content ratios, providing authentic, accurate, and reliable evidence for revealing the formation pathways and mechanisms of slip surfaces.

The experimental results show that: (1) At the micron scale, obvious boundaries can be observed between the sliding surface and adjacent surfaces, with non-uniform sliding surface thickness. In backscattered images at 10-nanometer resolution, the sliding surface structure is dense with small pores that are difficult to distinguish; (2) In a cubic slip zone soil sample measuring 17 m wide, 19 m high, and 500 m thick, the porosity of the sliding surface portion is 0.0331, while that of the adjacent surface portion is 0.0754, with the adjacent surface porosity being approximately 2.3 times that of the sliding surface; (3) Characteristic spectrum images and data from the energy spectrometer show that the characteristic elements of montmorillonite (Na, Ca, Mg) have obvious peaks on the sliding surface, with a steep diving drop near the boundary line, proving that montmorillonite is enriched on the sliding surface while none is detected on the adjacent surface; (4) The characteristic element K of illite is higher on the adjacent surface than on the sliding surface, indicating that illite content is significantly higher on the adjacent surface. Clear physical images and accurate energy spectrum data confirm significant differences in mineral composition and structure between the sliding surface and adjacent surface, and the low porosity of the sliding surface may be caused by pressure from the overlying soil mass.

For the first time, this paper reveals spatial differences in mineral composition, porosity, crystallinity, and particle size between sliding surfaces and adjacent surfaces using in situ experimental methods, providing reliable evidence for revealing sliding surface evolution pathways. To ultimately establish a cross-scale evolution model for sliding surfaces and soil masses, we need to conduct more comparative analyses of composition and structure differences, macroscopic strength, micro-nano scale structures, and mineral evolution dynamics processes between sliding surfaces and adjacent surfaces.

Keywords: Sliding surface; Focused Ion Beam Scanning Electron Microscopy (FIB-SEM); Mineral Analysis; Structure Reconstruction; Microporosity

Landslide occurrence represents a black-box process. To date, stability analysis and evaluation of landslides still rely on existing phenomenological strength theories such as the Coulomb-Mohr strength theory and criteria, which retrospectively deduce and back-calculate sliding surface strength after the fact. Meanwhile, in geotechnical engineering, soil deformation and failure widely adopt a series of elastic and plastic theoretical models and failure criteria based on continuous medium mechanics assumptions, such as the Coulomb-Mohr failure criterion, Duncan model, and Cambridge model. Although these models, established through phenomenological analysis of experimental data, have played significant roles in engineering practice, they cannot explain the mechanisms of geotechnical strength evolution under complex conditions or complete analysis calculations and predictions, because they fail to reflect the discontinuity and non-uniformity of geotechnical microstructures.

Soil mechanical properties are closely related to their mineral composition. Certain clay minerals, even in minimal amounts, can significantly affect the properties of clay materials. For example, clay containing a small amount (5%) of montmorillonite will have markedly different properties from another clay with identical composition but without montmorillonite. Additionally, the natural water content, moisture state, and type of exchangeable cations in clay minerals also greatly influence their properties. For instance, the properties of sodium montmorillonite and calcium montmorillonite differ substantially despite both being montmorillonite [1].

Rock and soil are nano-microscopically heterogeneous granular materials with complex and diverse failure mechanisms and patterns. Their performance and strength depend on the structure, arrangement, and movement of clay crystals. These structures include five scales and hierarchies: atomic structure, crystal lattice structure, grain structure, mineral particle aggregates, and macroscopic clay and rock units [2-3]. Rock and soil failure must cross these scales and hierarchies, and its failure laws should be the ultimate manifestation of the coupling of physical laws at these different levels. Therefore, rock and soil failure behavior should be studied using cross-scale methods.

The process of shear strength evolution in soil landslide sliding surfaces represents a cross-scale failure problem of slope soil under certain conditions, which systematically and profoundly reveals the laws of rock and soil deformation and failure under natural environments. The value of sliding surface strength evolution research lies not only in the field of landslide disasters but also provides an excellent platform for studying the engineering mechanical properties of rock and soil under special and complex environmental conditions.

1.1 Research Status of Sliding Surface Cross-Scale Studies

Clay mineral enrichment in sliding surfaces has been confirmed by many quantitative studies. The content of clay minerals and montmorillonite in landslide-prone strata is often higher than in non-landslide-prone strata, and the enrichment of montmorillonite on sliding surfaces is related to the weathering of illite into expansive illite-montmorillonite mixed-layer minerals [4-6]. Additionally, the authors' analysis of montmorillonite with different exchangeable cations shows that the elastic strength of sodium, potassium, and calcium montmorillonites differs significantly [7]. Mineral weathering, especially clay mineral weathering, reduces soil strength and causes landslides. The increase in montmorillonite or illite/montmorillonite mixed-layer minerals and the effective content of montmorillonite is a universal stimulating factor for landslide formation [8-10], even significantly affecting the C and values of loess and thereby changing the sliding collapse patterns of loess slopes [11].

Skempton plotted the relationship between clay particle (<0.002 mm) content and effective residual internal friction angle based on test data, noting that the residual strength of slip zone soil results from the directional arrangement of flat clay particles caused by shearing [12]. Zhou Pinggen et al. statistically derived the relationship between residual strength parameters and plasticity index and clay particle content for the Baota landslide [13]. Morgenstern studied the microstructure of kaolin and found the complexity of microstructural changes in sliding zone soil caused by shearing [14]. Yang Heping and Qu Yongxin used montmorillonite absolute content, mixed-layer ratio, and surface area—quantities related to microstructure and composition—as quantitative indicators for identifying regional geotechnical composition characteristics and swelling potential of landslide occurrence areas, providing clues for understanding the relationship between macroscopic and microscopic properties [15]. Xu Zemin et al. discussed the discontinuity of rock mass chemical weathering from micro-meso-macro three levels [16]. Yan Chunjie et al. used scanning electron microscopy and X-ray diffraction to study the microstructure and material composition of slip zone soil from 40 landslides in the Three Gorges Reservoir area and the Yellow River Xiaolangdi area, correlating them with landslide activity frequency, activity stage, and formation mechanism [6]. B.P. Wen & A. Aydin used optical microscopy and backscattered electron microscopy to comprehensively study the microstructure of a natural landslide slip zone soil, finding that changes in porosity, flat clay particle content, and particle arrangement characteristics are three important indicators reflecting changes in the mechanical properties of slip zone soil [17]. Bai X. conducted comprehensive and systematic research on the microstructure of a natural slip zone soil [18]. Zhang Xian tested the relationship between clay content and strength under certain water content conditions, proving that clay strength is closely related to clay type, composition, and water content [19]. Zhao Yu used modern research methods including electron probe microanalysis, X-ray diffraction, infrared spectroscopy, scanning electron microscopy, direct shear tests, and autoclaves to calculate and analyze differences in clay mineral composition between sliding surfaces and adjacent surfaces of typical landslides in the Three Gorges Reservoir area under acid rain conditions, their semi-quantitative molecular formulas, and speculated possible evolution pathways and landslide occurrence mechanisms, establishing a preliminary chemical-plastic mechanical model and conducting preliminary analysis of sliding surface strength evolution using chemo-mechanical coupling cross-scale methods [4, 20-21].

1.2 Research Status of Soil Microstructure Mechanics

In the field of soil microstructure mechanics, since Terzaghi first proposed the honeycomb structure of soil in 1925, noting that microstructure should be considered when evaluating the engineering geological properties of clayey soils and rocks, scholars worldwide have conducted multifaceted research on the relationship between soil deformation failure and its microstructure.

Academician Shen Zhujiang pointed out that the mathematical model of soil structure is the core of 21st-century soil mechanics [22] and proposed the building block and improved binary medium models. Xie Dingyi proposed a concise and practical structural parameter—comprehensive structural potential—arguing that the fundamental task of soil structure research is to find a quantitative indicator that can comprehensively reflect the arrangement characteristics and bonding features of soil particles. This indicator should simultaneously have a close connection with soil deformation and strength to establish and describe the basic laws between them [23].

Currently, there are two main types of influential microstructure models: one is the overlapping sheet and micro-slip surface model developed from the classical plastic slip theory established by Batdorf and Budiansky (1949), which is built from the perspective of soil microstructure and receives considerable attention in the international soil mechanics community [24]; the second is the particle simulation model established by Cundall (1971) and Strack (1979), which has recently been applied to constitutive relationship models for composite materials such as cement, fiber, and sand [25, 26]. In China, Dr. Shi Bin used the first type of micro-mechanical model to establish a micro-mechanical model for anisotropic cohesive soil (soft soil) creep, achieving good fitting results [27].

Additionally, Hu Ruilin, Wu Yixiang, and older-generation scholars including Zhang Zonghu, Wang Youlin, Tan Luorong, and Cheng Changbing have conducted valuable work on soil microstructure and strength constitutive model research [28-29]. Hong Baoning systematically and deeply studied the relationship between microstructural changes and shear strength indicators of cohesive soil, cement soil, and ecological soil under continuous loading and erosion environments, attempting to explain the intrinsic structural mechanisms of macroscopic mechanical properties [24].

Clay particles (mostly composed of minerals or mineral aggregates) are the basic structural units of soil and may become carriers and transmission media for structural stress or spatial antibodies for structural stability. Soviet soil mechanics researchers applied several tons or even dozens of tons of pressure per square centimeter to soil samples in 1936 and 1955, yet clay mineral crystals showed no obvious cracks. Morgenstern’ s aforementioned experimental analysis of the cross-scale microstructure of kaolin also showed that deformation occurred between particles rather than within particles [14], leading to the conclusion that differences in clay mechanical properties are not primarily caused by monomer mineral composition but depend on mineral aggregates, especially the contact forms between particles. The contact form here refers to the physical and mechanical properties and geometric characteristics of interparticle bonds. Osipov et al. believed that only the nature of interparticle forces can reflect the essence of particle connection. Therefore, he advocated classifying particle connection types based on interparticle distance and force strength to quantify clay structural characteristics [30].

Chen Tao et al. analyzed clay mineral microstructure using high-resolution transmission electron microscopy [31]. Liao Yiling, Zhou Xunhua, and Gao Guorui used energy spectrometers and scanning electron microscopy to analyze the microstructure of red clay, confirming that mineral sheets in red clay are firmly connected and that shear failure of red clay originates from the destruction of structural connections between mineral particles (i.e., particle clusters, aggregates of dozens or hundreds of clay mineral sheets) [32-33]. This conclusion was successfully applied to red clay and marine sediment clay engineering practice [34]. Zhu Lijun et al. systematically studied clay minerals in carbonate rock red clay in Guizhou using X-ray diffraction, infrared spectroscopy, differential thermal analysis, transmission electron microscopy, and scanning electron microscopy, discussing the formation mechanism and evolution sequence of clay minerals based on red clay microstructural characteristics [35].

Moreover, clay minerals are layered silicate minerals composed of orderly arranged atoms and ions. Many of their physical and chemical properties are related to the behavior of a relatively small number of outer-layer electrons involved in chemical bonding. The combination of chemical bonds and structure can explain mineral physical properties [36]. Nadean et al. (1983) [46] and Lee and Peacor (1984) [47] found that clay particles are extremely fine with relatively stable compositions, and that clay alteration occurs not through structural changes but through dissolution and replacement, such as the transformation of montmorillonite to illite in mudstone, which is consistent with our findings on the evolution of clay composition in sliding surfaces and adjacent surfaces in the Three Gorges area [4, 20-21].

In recent geotechnical microstructure research, K.C. Bennett et al. quantitatively analyzed the nano-microscopic mechanical properties, anisotropy, and heterogeneity of shale through nanoindentation experiments and scanning electron microscopy [37]. J. Iqbal et al. conducted ring shear tests on Luojiazui landslide samples and observed the microstructure during shearing using SEM, finding that shearing transformed the soil from a honeycomb structure to a layered structure formed by layered clay aggregates with good orientation [38]. M. Schäbitza et al. studied the microstructure, mineral composition, and texture of three landslide samples in southern Gansu, noting that the appearance of graphite and pyrophyllite with extremely low friction coefficients is particularly important for reducing the frictional strength of landslides. They also found that the reduction in clay particle size in clayey sliding zone materials is mainly caused by mechanical wear, while the reduction in calcite and quartz particle size in slip zone soil results from pressure dissolution and fragmentation. The article also reported for the first time the preferential orientation of silicates in local shear zones of landslides [39]. Sho Kimura et al. conducted ring shear tests on quartz sand under high vertical stress, finding that total porosity showed no significant reduction under low stress conditions but changed dramatically under high stress conditions. Further observation of pore structure and particle gradation revealed that pore diameter and particle size control changes in sample permeability [40]. Tang Wen et al. analyzed the pore structure of slip zone soil through mercury intrusion tests, finding that pores are mainly small pores and transitional pores [41]. These studies fully demonstrate the correlation between soil microstructure and its macroscopic mechanical properties.

Meanwhile, recent research continues to focus on the influence of clay minerals on the strength of slip zone soil. Wu Ruian et al. used X-ray diffraction and scanning electron microscopy to find that the main clay minerals in the weak interlayer of the Xiangcheng Primary School landslide are illite and illite-montmorillonite mixed-layer minerals, with microstructures dominated by flaky shapes, some showing layered directional arrangement [42]. Zhou Chunmei et al. found high montmorillonite content in slip zone soil through X-ray diffraction, with SEM images showing obvious directional arrangement characteristics of minerals and well-developed microcracks and micropores between minerals [43]. Zhao Yu and Tao Yeqing analyzed the components of slip zones and adjacent surfaces and ion content changes in groundwater solutions in slip zones, discussed water-soil chemical interactions in slip zones, and explored the effects of different occurrence environments on slip zone soil through laboratory immersion experiments [44-45].

Changqun Zuo et al. conducted tests on tuff residual soil under different water content conditions using XRD, direct shear tests, and SEM, finding clay mineral enrichment mainly consisting of montmorillonite and illite with layered structures. They noted that water content and wet-dry cycle conditions significantly affect soil structure, primarily due to soil disintegration caused by water-sensitive minerals [46]. Shuai Zhang et al. immersed red bed soft rock landslide samples in distilled water and found that clay mineral particles changed from face-edge and face-face contacts to edge-edge and face-edge contacts, causing clay minerals to become loose and porous. They concluded that the increase in water film thickness and lattice expansion of illite particles is the basic mechanism of landslide failure [47].

The above experimental analyses do not reflect the spatial distribution and changes of mineral composition and structure in sliding surfaces and adjacent surfaces, and thus cannot restore the mineral evolution pathways of sliding surfaces. Therefore, this study adopts fresh, non-weathered slip zone soil to conduct in situ analysis of elements, mineral composition, crystallinity, pores, and their spatial distribution differences between sliding surfaces and adjacent surfaces, aiming to reveal the physical pathways of sliding surface formation.

2 Geological Background

Red beds are continental sedimentary rock layers composed of interbedded sandstone, mudstone, and shale with reddish hues, widely distributed in southwestern, northwestern, central, and southern China. The red beds in southwestern China are the most extensive and representative, primarily consisting of Jurassic and Cretaceous strata. The special interbedded structure and water-sensitive weak interlayers of mudstone and shale make red beds typical landslide-prone strata. In the central Sichuan Basin, low mountain and hilly areas at basin margins (including the Three Gorges area of Chongqing), and the Panxi and western Yunnan red bed distribution areas in medium-high mountain regions, numerous landslide disasters frequently occur during rainy seasons [48-50], often causing serious casualties and property losses. Additionally, in infrastructure construction projects, artificial excavation and embankment filling often induce large-scale red bed landslide disasters [51-52], affecting normal construction progress. To prevent and control landslide disaster losses in red bed areas, this study aims to reveal the occurrence and development pathways and mechanisms of red bed landslides based on cross-scale theory and methods, laying a theoretical foundation for landslide disaster prediction methods and prevention measures.

The sampling site is located at Danjiagou, a suburban county of Dayi, Chengdu City, Sichuan Province. The slope is a medium-weathered, bedding-parallel slope of Jurassic red bed sandstone and mudstone interbeds. The landslide front edge elevation is 547.80 m, the rear edge elevation is 676.60 m, with a relative height difference of 128.80 m, an average slope of 27°, and bedrock attitude of 270° 29°. Weathered zones with thick fissured clay formed along bedding and vertical joint directions. Induced by more than 20 days of prior rainfall, a landslide occurred on August 19, 2018.

[Figure 1: see original paper] Danjiagou Landslide Panorama

[Figure 2: see original paper] Distribution map of sampling points on the Danjiagou landslide sliding surface. The yellow circles with numbers indicate sample positions and sample numbers. Sample D6 was taken outside the profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1 Sample Preparation

Fresh sliding surface and adjacent surface samples without post-weathering were collected in the field and naturally dried indoors. Due to the requirements of electron microscopy observation and the non-conductive nature of dried clay, the sample surfaces were argon-ion polished and coated with a conductive Pt layer. A magnetron sputtering coater (Lab 18) was used to coat the argon-ion polished samples with a conductive platinum (Pt) layer, with a polishing area of approximately 0.5 cm × 0.5 cm.

3.2 Experimental Equipment, Principles, and Parameters

To conduct in situ 2D and 3D structure and composition analysis of sliding surfaces and adjacent surfaces, this study primarily utilized the Helios Nano Lab-650 focused ion beam scanning electron microscope (FIB-SEM), AMICS automatic mineral analysis software, and Avizo Fire software.

The FEI Helios 650 series dual-beam scanning electron microscope (FIB-SEM) uses a gallium ion beam for continuous cutting of experimental samples, while using an electron beam to image the cut sections at an imaging voltage of 5 kV and maximum resolution of 0.8 nm. For subsequent analysis, this experiment used backscattered electron (BSE) mode for scanning imaging. Additionally, the equipment is equipped with an EDAX energy spectrometer for mineral composition characterization, with point scanning, line scanning, and area scanning modes available at an acceleration voltage of 15-30 kV and dead time of 20%-30%.

The AMICS (Automatic Mineral Identification and Characterization System) software identifies mineral species by comparing collected sample element composition energy spectrum data with the mineral database within the software. It can also combine high-resolution scanning electron microscope images to determine the spatial distribution of each mineral component.

Avizo Fire is an advanced 3D visualization and analysis application software that can integrate scanning electron microscope images collected by FIB-SEM equipment to achieve 3D structure reconstruction of samples. Based on the different gray values of each mineral component and pores, it extracts structural parameters from the reconstructed structure to obtain the spatial distribution of mineral composition, structure, and porosity in sliding surfaces and adjacent surfaces.

3.3 Experimental Procedures

First, representative samples were selected and cut into appropriately sized thin sections, with surfaces polished using argon ions. Since the experimental samples are soil with non-conductive characteristics, a thin gold layer was sprayed on the polished surface to enhance conductivity for electron microscopy observation of the region of interest. The processed samples were then fixed on sample stages with conductive adhesive.

The samples were placed in the focused ion beam scanning electron microscope sample chamber and vacuumed. The MAPS mode was then used to select regions of interest on the sample surface, typically 10 m × 10 m. The sample stage position was adjusted to make the sample perpendicular to the ion beam, while a platinum layer was sprayed on the region of interest surface to prevent ion beam damage. The ion beam was then used to etch the front and both sides of the intended imaging area within the region of interest to form a "nose tip" for subsequent 3D structural imaging (as shown in Figure 1).

Before cutting, an "X" mark was made with the ion beam near the region of interest for ion beam alignment during the cutting process. The subsequent 3D imaging + EDS (FIB-SEM + energy spectrometry) is based on the combined action of electron and ion beams. According to experimental objectives, the ion beam cuts at 10 nm intervals, and the electron beam performs backscattered electron imaging on the exposed cross-section. After repeated "cutting-imaging" cycles, 500 frames of scanning electron microscope backscattered electron images were obtained. The obtained energy spectrum data were automatically imported into AMICS software for mineral composition determination of sliding surfaces and adjacent surfaces. The 500 frames of backscattered scanning electron microscope images were reconstructed into 3D structures using Avizo Fire software. Based on AMICS analysis results, gray value differences, and image processing tools, the mineral composition, content, characteristic mineral area, volume, and pore area and volume percentages of slip zone soil were measured and calculated.

This experiment breaks the past limitation of being able to only extract powders from sliding surfaces and adjacent surfaces for composition analysis without being able to conduct in situ composition and structure analysis. It performs 3D morphology and energy spectrum analysis on slip zone soil, achieving in situ analysis of the spatial distribution of clay mineral composition, content, microstructure, and pores in slip zone soil. This represents an experimental technical breakthrough for landslide mechanism research.

4.1 3D Morphological SEM Images of Slip Zone Soil Structure and Composition

The "nose tip" section shown in Figure 1 was continuously cut and imaged at 10 nm intervals 500 times, forming a series of SEM images that clearly present the structure, composition, and pore distribution of slip zone soil. Figure 1b is a 3D stereogram of the etched slip zone "nose tip" section, and Figure 1c is a side view of this section. The figures show clear stereoscopic images of slip zone soil and reveal clear interfaces and structural differences between the sliding surface and adjacent surface. The sliding surface width is approximately 1.2–4.9 m, with a clear boundary between the sliding surface and adjacent surface. The sliding surface material has a dense structure with fewer pores, while the adjacent surface has more pores, a loose structure, and higher porosity.

[Figure 3: see original paper] Schematic diagram of FIB-SEM technology principle and 3D stereogram of slip zone soil sample: (a) Schematic diagram of cutting and imaging in FIB-SEM system, where the ion beam cuts the sample and the electron beam images; (b) 3D backscattered imaging of the "nose tip" section cut from slip zone soil sample; (c) Side view of cut sample in backscattered mode, with the sliding surface within the red box and the remaining portion being the adjacent surface.

Figure 2a shows a series of scanning electron images obtained in the experiment, including secondary electron images (SE, Figure 2a) and backscattered electron images (BSE, Figure 2b), which serve different purposes. The former better displays surface structure and is more helpful for morphology research, while the latter can show differences in atomic number, displaying compositional differences in images.

[Figure 4: see original paper] Figure 2: (a) Secondary electron (SE) image of slip zone sample; (b) Backscattered electron (BSE) image of slip zone sample.

The obtained SEM images were imported into 3D reconstruction software AVIZO for reconstruction, yielding series images and 3D stereograms of each component, as shown in Figure 3a. In Figure 3b, yellow represents calcite, green represents pores, and off-white represents other components (matrix).

[Figure 5: see original paper] (a) Yellow portion: calcite; Green: pores; Off-white: matrix (other components).

By making the 3D image transparent (eliminating information on other components), the spatial distribution state and volume content ratio of the analyzed components or pores in slip zone soil can be displayed more clearly and intuitively. Figure 3b shows the spatial distribution state and volume percentage of calcite in slip zone soil.

Thus, we can calculate the volume percentage of various components in slip zone soil, including the volume percentage of pores.

Volume percentage of components in slip zone soil

4.2 Porosity Distribution in Slip Zone Soil

Based on 3D structure reconstruction and pore measurement, a cubic slip zone soil body measuring 17 m wide, 19 m high, and 500 m thick contains a total of 22,408 pores. Data on pore length, width, area, and volume are provided in Appendix 2, with the largest and smallest pores shown in Table 2 :

Using PerGeos Fire software, based on 3D test results, the spatial distribution state of the substrate (Figure 4a) and pores (Figure 4b) were obtained, and the sliding surface porosity was calculated to be 0.0331 (blue portion), while the adjacent surface porosity is 0.0754 (purple portion).

[Figure 6: see original paper] Spatial distribution state of substrate (a) and pores (b) in slip zone soil.

4.3 Energy Spectrum Data Analysis

The polished sample surface is flat, and the authigenic morphology of minerals disappears, allowing only rough distinction between minerals based on gray values. Combining X-ray energy spectrometer results for micro-area element analysis and based on the uniqueness of mineral atomic ratios, mineral and pore point, line, area, and volume distributions can be more accurately determined.

The experiment obtained characteristic spectral lines in micro-areas mainly as K and K lines. The K line represents characteristic X-rays released when excited electrons in the L shell outside the atomic nucleus transition to the K shell and lose energy. The K line represents characteristic X-rays released when excited electrons in the M shell outside the atomic nucleus transition to the K shell and lose energy. Since the K line has lower intensity than the K line, the K line intensity is generally used for element content calculation.

During this experiment, 13 line scans were performed on 4 different cross-sections, with a measurement point spacing of 100 nm during scanning. Montmorillonite particle size is approximately 2–5 m, and this line scan density can meet the requirements for mineral component analysis based on characteristic elements. The signal intensity of major elements was recorded to reflect the spatial variation trend of relative content of these elements perpendicular to the sliding surface and adjacent surface.

[Figure 7: see original paper] (a) SE electron microscope photo; (b) Energy spectrometer line scan results; (c) Point scan content data; (d) Major element legend.

To reveal the mineral variation trend perpendicular to the sliding surface direction, potassium and sodium elements were separately analyzed as characteristic elements of illite and montmorillonite.

In the potassium element distribution map 1, K content fluctuated slightly in the first 1.3 m, increased significantly at 1.3–2.3 m, and the average K content in the first 1.3 m was significantly lower than the average value after 2.3 m.

In the potassium element distribution map 2, K content fluctuated slightly in the first 1.1 m, increased significantly at 1.1–2 m, decreased obviously at 2–2.5 m, and increased again at 2.5–3.2 m. SEM images show a microcrack at 2 m, and this K content variation trend is suspected to be caused by mineral component changes. Overall, the average K content in the first 1.1 m is significantly lower than the average value after 3.2 m.

The sodium element distribution map shows a phenomenon of rapid decrease followed by stable fluctuation in Na content. The images show that Na element content in the sliding surface portion is much higher than in the adjacent surface.

Using the energy spectrometer, we performed 13 line scans at 1-micron intervals on sliding surfaces and adjacent surfaces to quantitatively analyze the spatial distribution of elements and mineral components. Experimental images and data clearly and reliably confirm our speculation: montmorillonite is significantly enriched on sliding surfaces with thickness <5 m, while illite content is significantly higher on adjacent surfaces.

5 Conclusions and Discussion

The FIB-SEM images and energy spectrometer data and curves of slip zone soil (sliding surface and adjacent surface) show:

1. At submicron scales, the structural difference between sliding surfaces and adjacent surfaces is obvious. The macroscopically visible paste-like sliding surface appears structurally dense with low porosity at micron scales and exhibits clear horizontal orientation. At micron scales, it resembles a horizontal layered fine paste covering the non-directionally distributed adjacent surface. SEM photos, energy spectrometer, SE, and BSE images show the sliding surface thickness is approximately 3.319 m, with a denser structure, lower porosity, and smaller pore sizes compared to the adjacent surface. This indicates that sliding surface strength reduction is not caused by porosity changes and has little relationship with porosity, but rather results from changes in clay composition.
2. Sliding surface thickness was measured and marked (see Fig. 1-13) at fourteen test points, where point, line, and area element and mineral component analysis tests were conducted.
3. Based on element ratios, it can be calculated that montmorillonite content is significantly higher on sliding surfaces, while illite content is significantly higher on adjacent surfaces. The distribution of montmorillonite and illite basically coincides with the microstructural interface between sliding surfaces and adjacent surfaces, with individual differences being insignificant.

6 Conclusions and Future Work

This study utilizes the uniqueness of mineral atomic ratios to identify mineral species and uses X-ray diffractometers and energy spectrometers to determine mineral content, pore ratios, and the spatial distribution of minerals and pores.

Conclusions: Appropriate conclusions should be drawn based on research objectives and results, and the value of the research and issues for future discussion should be identified. The expression of rock mass strength criteria is a key fundamental theoretical issue in rock mass engineering geological dynamics. Current commonly used rock mass strength criteria mostly describe the compressive, shear, or tensile capacity of rock and soil masses at the moment of failure, without considering the progressive failure process of rock masses, making it difficult to describe the real mechanical behavior of rock masses in nature and laboratories, such as the formation and evolution of deep cracks in Jinping slopes and the brittle "wedge-shaped" rockburst failure of deep-buried caverns. Proposing a strength model that can consider progressive rock mass failure is of great significance for research in this field.

Due to current limitations in microstructure analysis resolution, the characterization and quantitative evaluation technology of slip zone soil porosity remains imperfect, resulting in insufficient understanding of the distribution, evolution, and influencing factors of nanopores in sliding surfaces and adjacent surfaces, which seriously affects the role and contribution weight of porosity during sliding surface formation. The authors will improve nano-analysis technology to establish a quantitative characterization method for clay mineral composition content and pores in slip zone soil, and conduct research on nanometer pore structure, genesis, controlling factors, and evolution characteristics in sliding surfaces and adjacent surfaces within slip zone soil, attempting to provide a theoretical basis for the storage mechanisms of shale gas and coalbed methane.

We believe that image studies of composition and structure in slip zone soil confirm that sliding surface formation has experienced potassium ion loss and interlayer water adsorption. Combined with our field groundwater data and X-ray diffraction data of sliding surfaces and adjacent surfaces, as well as pore distribution changes, we have reason to determine that the loss of interlayer potassium ions in illite is the most important process of mineral evolution within slip zone soil and plays a decisive role in sliding surface formation.

In the future, the research team will strengthen research in three aspects:

1. **Image Analysis Technology for Sliding Surfaces and Adjacent Surfaces:** Using high-resolution characteristics and analysis methods such as cross-section analysis, phase analysis, and particle size analysis, we will strengthen micro-area observation and analysis technology for slip zone soil, further improving information on mineral types and content, pore size, shape, distribution, and particle contact conditions. Focusing on changes and distribution of surface porosity, we will reveal pore distribution and variation in slip zone soil and analyze mineral evolution dynamics mechanisms, laying a foundation for quantitative research on sliding surface formation mechanisms.
2. **Problem-Solving Approaches:** However, as the research is in its initial stage, insufficient data exist to clarify how different mineral components

and their evolution processes affect sliding surface strength and to what degree. Microscopic image analysis technology is advancing rapidly, and our research has been striving to improve testing accuracy and quantitative analysis. We believe that with improved instrument precision and data interpretation methods, next year we will use FESEM-BIB to study changes in mineral types, content, and pores during the transformation from adjacent surfaces to sliding surfaces in slip zone soil, and quantitatively statistics particle shape, roughness, interparticle bonding force, pore size distribution, surface porosity, and pore area. FESEM-FIB combined with section preparation and observation can ensure section flatness and high image resolution, enabling deeper observation of points of interest more quickly and freely, and allowing 2D observation or 3D reconstruction of certain areas as needed.

Slip zone soil image analysis technology undoubtedly has intuitive and reliable advantages in revealing sliding surface formation pathways. However, current research remains at the qualitative stage. In the future, we hope to combine quantitative and 3D characterization to improve the ability and quality of information acquisition from slip zone soil image research, integrate slip zone soil image information with theoretical issues such as formation dynamics mechanisms, establish a slip zone soil image evaluation process, and from an intuitive physical meaning, establish a cross-scale mechanism model for sliding surface formation.

The main purpose of this paper is to attempt to establish a new method for fine detection and quantitative evaluation of clay strength evolution through image analysis and data analysis of clay mineral composition, content, structure, and distribution change characteristics in slip zone soil (sliding surface and adjacent surface), reveal sliding surface formation and evolution mechanisms and their controlling factors, and thereby clarify the influence mechanism of composition and structure on clay mechanical behavior.

Experimental Data and Image Explanation: Spatial distribution differences in sliding surface mineral composition, content, and porosity reflect clear layering between sliding surfaces and adjacent surfaces in slip zone soil, with obvious differences in mineral composition between sliding surfaces and adjacent surfaces, providing clear physical images and reliable test data for sliding surface formation pathway and mechanism analysis. However, due to fine mineral particles and low conductivity, secondary electron images cannot clearly display slip zone soil surface structure, affecting research on morphological structure, cement composition, and interparticle connection states. Backscattered electron (BSE) image gray value differences are also not obvious enough to clearly show atomic number differences. Future work needs to further improve equipment spatial resolution and gray value differences to complete analysis of mineral composition differences between sliding surfaces and adjacent surfaces.

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Note: Figure translations are in progress. See original paper for figures.