Industry Science and Engineering Vol. 3 No. 8, 2026

Study on Differential Weathering and Induced Failure Mechanism of High and Steep Slopes with Interbedded Soft and Hard Rocks

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Abstract: Differential weathering of high and steep slopes composed of interbedded soft and hard rocks serves as a typical trigger for geological hazards. Weathering processes are mainly categorized into physical, chemical and biological weathering. Multiple factors including rock mineral composition, rock mass structure and water-rock interaction are coupled to dominate the differential weathering evolution. Representative rock mass samples were tested and analyzed in this work, focusing on mineral components and their contents, cement types and cementation strength, as well as macroscopic and mesoscopic structures of rocks, to interpret the formation mechanism of differential weathering. The results demonstrate that clay mineral content, cement properties and cementation degree, together with macroscopic rock mass structure, exert controlling effects on differential weathering, and these parameters can be adopted as critical indicators to characterize the weathering response of rocks. Temperature analysis reveals that short-term temperature variation hardly imposes direct influences on the intrinsic weathering properties of rocks. Nevertheless, temperature can remarkably aggravate differential weathering between soft and hard rock layers by modulating water-rock interaction. Combined with engineering cases and FLAC^{3D} numerical simulations, it is found that the risk of collapse instability of interbedded soft-hard rock slopes rises substantially once rock cavities are formed due to progressive differential weathering. This study preliminarily identifies the major hazard modes induced by differential weathering, and provides theoretical support and scientific references for the engineering prevention and mitigation of potential geological hazards in interbedded soft and hard rock slopes.

Keywords: High and Steep Slope; Interbedded Soft and Hard Rocks; Differential Weathering; Numerical Simulation.

1. Introduction

The weathering degree depends not only on the intensity of weathering agents, but is also jointly controlled by regional climate, lithology, geological structure, topography and hydrogeological conditions[1,2]. Thus, it is essentially a dynamic geological process driven by multiple factors[3]. Weathering modifies rock masses in a gradual manner. The integrity of the rock mass is first damaged, with pre-existing fractures expanding and new ones developing, so that an originally intact mass gradually disintegrates. This is followed by changes in mineral composition and chemistry, during which secondary minerals form and the original constituents of the rock are altered. Meanwhile, water resistance weakens while hydrophilicity and permeability increase, mechanical strength declines, and the engineering geological properties ultimately deteriorate.

In nature, weathering agents act in combination. Owing to differences in rock composition, structure, and the local climate and topography, weathering is not only ubiquitous but also spatially uneven, which is known as differential weathering. When rocks of different mineralogy, fabric, and jointing occur together, their contrasting resistance to weathering and unequal rates of denudation give rise to differential weathering; the Danxia landform, karst topography, spheroidal weathering of granite, and ventifacts in deserts are all typical

expressions. Three circumstances can be distinguished: the same lithology weathering to different degrees under varying climate or topography; different lithologies weathering differently under identical external conditions; and the same lithology, with differing fabrics, developing spheroidal or cavernous weathering.

Considerable research has been devoted to the degree, evaluation, and origin of weathering. Kong[4] proposed early on that weathering can be assessed in the field by eye through changes in color, luster, mineral composition, and the degree of fragmentation; these criteria remain widely used for their simplicity. Subsequent work has shifted from qualitative description toward quantitative characterization. Indicators such as rock color, mineral composition, density, porosity, and uniaxial compressive strength; the number, spacing, aperture, and infilling of structural planes; and rock mass integrity, structure, and quality have all been used for weathering zoning. On this basis, Zhang et al. proposed a comprehensive qualitative zoning scheme, while Feng[5] further established quantitative relations among the rock quality designation (RQD), fracture spacing, and the integrity coefficient of the rock mass. Concepts such as the weathering index, weathering coefficient, and weathering rate have also been introduced to characterize silicate weathering intensity, wave-velocity attenuation, and the thickness of weathered material over time. These studies show that the higher the uniaxial compressive strength, the stronger the weathering resistance, and that the time required for different rocks to reach the same weathering depth may differ by as much as two orders of magnitude.

These efforts provide a foundation for understanding weathering, yet most of them focus on a single lithology such as granite or karst rock. Systematic understanding is still lacking for high and steep slopes composed of interbedded soft and hard rocks, particularly how differential weathering initiates rock cavities and subsequently drives collapse instability. Taking the interbedded soft–hard high-cut slopes, this paper combines field investigation, laboratory slake and mineral tests, scanning electron microscopy, and FLAC^{3D} numerical simulation to examine the mechanism of differential weathering and its role in triggering geohazards.

2. Types and Influencing Factors of Differential Weathering

2.1 Types of Differential Weathering

General weathering, differential weathering can also be classified into three types based on the nature of the agent: physical weathering, chemical weathering, and biological weathering. These three processes often occur interdependently in the slope, but they exhibit different relative intensities under different rock types and climatic conditions [6].

Physical weathering refers to the type of weathering where the chemical composition of the rock remains largely unchanged during the mechanical breakdown process [7]. Its causes include the relaxation of rock layers due to gravity and stress release, the separation and fatigue failure of mineral particles with different thermal expansion coefficients in regions with large temperature differences, the ice splitting process in cold regions, the crystallization of salts in arid areas, and the alternation of dry and wet conditions. The common feature of these processes is that they do not change the mineral composition of the rock, but mainly cause the rock to transform from a whole to fragments and debris. The factors that trigger physical weathering mainly include temperature changes, water, ice, wind, crystal growth stress, and biological activities. In cold and arid regions such as the polar and temperate zones, physical weathering usually dominates.

Chemical weathering refers to the type of weathering where rocks undergo chemical decomposition under the influence of oxygen, water, various acids dissolved in water, and biological processes [8]. When rocks come into contact with groundwater and air, water not only dissolves the mineral components within the rocks but also reacts with the air to form a reaction solution. This solution can then continue to interact with other minerals in the rocks, and this process is closely related to soil formation. Chemical weathering mainly involves dissolution, hydrolysis, hydration, and oxidation, causing changes in the mineral composition and chemical composition of rocks, and forming new mineral combinations. Chemical weathering is the dominant type of weathering in tropical and subtropical regions.

Biological weathering refers to the chemical effects exerted by living organisms within the rock and soil matrix during their existence and

reproduction, which indirectly alter the structure and composition of the rock. The damage caused by organisms to rocks involves both mechanical and chemical processes, with the chemical process being more significant. Almost all chemical weathering is related to biological action: the organic acids secreted by organisms can promote and accelerate the chemical decomposition of rocks, and organisms can selectively absorb certain elements and convert them into organic compounds; the gases such as carbon dioxide and oxygen produced by biological metabolism also affect the weathering process.

There is a complementary relationship between physical weathering and chemical weathering. Physical weathering increases the surface area of rocks, thereby providing more reaction interfaces for chemical weathering and accelerating the rate of chemical weathering. Therefore, physical weathering constitutes a controlling factor for chemical weathering to a certain extent.

Dividing weathering into three types is a common practice. However, if strictly classified according to the causes of weathering, it is more reasonable to categorize it into physical weathering and chemical weathering, because the biological weathering caused by plants and animals ultimately still needs to be achieved through mechanical fragmentation or chemical reactions, and it is not an independent third force independent of physical and chemical processes.

2.2 Influencing Factors of Differential Weathering

The influencing factors of differential weathering include the mineral composition of rocks, the structure and structure of rock masses, topographic and geomorphic conditions, climatic conditions, and the role of water.

2.2.1 Influence of rock mineral composition

Due to the varying weathering resistance of different minerals, there is a difference in weathering among different minerals of the same rock, or differences in weathering degree and nature between different rocks, resulting in weathering variations. Generally, based on the different weathering rates, different minerals can be roughly classified into three stability grades, as shown in Table 1.

Table1. Stability Classification of Common Rock-Forming Minerals

Unstable minerals	Secondary stable minerals	stable minerals
Olivine	Biotite	Quartz
Hematite, pyroxene	Kyanite	Tourmaline
Basic plagioclase	Medium-acid plagioclase	Corundum
Limestone	Black mica	Zircon
Calcite	Illite	Kaolinite
Metal sulfides	Magnetite, Chlorite, Phosphorite	High-priced iron-manganese

According to their resistance to weathering, common rock-forming minerals can be classified into three categories: unstable, secondary stable, and stable. Unstable minerals include soluble salts and those that are prone to oxidation or carbonation, with a fast weathering rate and generally not remaining in the form of fragments in the sediment; semi-stable minerals decompose mainly through hydrolysis, slight oxidation, or carbonation, maintaining moderate chemical stability and often being preserved in the form of rock fragments or single crystals; stable minerals have extremely low solubility under normal weathering conditions, such as quartz, rutile, hemihydrates, and clay minerals, and are mostly retained in the form of fragments.

Rock, especially mudstone, often contains a large amount of clay minerals. The soil particles are extremely fine, mostly in sheet form, and are highly active, being an intrinsic factor controlling the deformation, strength, and disintegration expansion properties of the rock. Common clay minerals include kaolinite, illite, and montmorillonite: kaolinite forms through the weathering of feldspar, with hydrogen bonds connecting the crystal layers, making water difficult to enter, and the soil particles are relatively thick; illite is the weathering product of mica in an alkaline environment, with potassium ions connecting the layers, and the soil particles are thin and delicate; montmorillonite forms through further weathering of illite or volcanic ash weathering, with weak interlayer connections, allowing water molecules to easily enter and causing crystal layer expansion, and the soil particles are extremely thin. The specific surface area of these three types of minerals is the largest for montmorillonite, followed by illite, and the

smallest for kaolinite.

Among them, montmorillonite has a large specific surface area and weak interlayer bonding force. When exposed to water, it undergoes significant lattice expansion, which is the most important mineral factor causing rock disintegration, softening, and expansion deformation, and is also a key test object when studying differential weathering and the water properties of rocks.

2.2.2 Influence of rock mass structure

The rock mass structure is typically classified into four types: overall block structure, layered structure, fractured structure, and disperse structure. The spacing of the structural planes decreases successively, and the integrity coefficient decreases successively. According to the formation cause, the structural planes can be divided into primary structural planes, structural planes formed by tectonics, and epigenetic structural planes. The control of rock mass structure on differential weathering is mainly achieved by controlling the transportation channels of water and wind.

Fault zones or joint-intensive zones often form deep weathering channels; even small joints can cause intense chemical weathering on both sides. Joints and fractures provide channels for weathering to extend from the surface to the interior, making the weathering depth much greater than simple surface weathering.

For slopes with alternating layers of soft and hard rocks, the structural planes in the hard rock generally cannot penetrate the entire stratum and have low connectivity, making it difficult to form a continuous groundwater seepage network. However, after the soft rock loses water, it is prone to generate dry shrinkage cracks on the surface and expand inward, causing the rock mass to break and accelerating the weathering and disintegration after immersion in water; when water is encountered again, the fractures first fill with water and expand, the strength sharply decreases, the soft rock undergoes plastic flow extrusion, and ultimately the stability of the entire interlayer rock mass decreases and the weathering process accelerates. In addition, under surface and underground excavation conditions, residual joints and their combinations often cause local damage; the formation of karst caves in limestone areas is essentially the result of differential weathering along the structural planes.

2.2.3 Influence of topography and landforms

The influence of topography and landform on differential weathering is mainly manifested in the slope gradient. High and steep slopes are not only places where differential weathering is highly developed, but also necessary terrain conditions for the formation of collapses and rockfalls. From the perspective of regional landforms, collapses mostly occur in mountainous and plateau areas; from the perspective of local terrain, they are concentrated in steep canyons, gully banks, and deep river valleys, usually occurring on slopes with a large slope angle, a slope height exceeding 30 meters, and uneven slopes.

Topographic height difference also affects the relative strength of physical weathering and chemical weathering by controlling the erosion rate. On flat terrains or quasi-plains with gentle topography in tropical and subtropical regions, surface runoff is sluggish and water-rock interaction continues, often forming thick weathering shells, and local areas may even be rich in kaolin and bauxite deposits; while in steep and highly dissected mountains, surface drainage conditions are good, and chemical weathering is inhibited. In high-altitude areas with large topographic height differences and rapid erosion and erosion, weathering products often fail to undergo sufficient chemical decomposition before being transported, and physical weathering thus dominates; in low-lying areas with slow erosion rates, chemical weathering proceeds relatively thoroughly.

2.2.4 Influence of water

Water is one of the most active factors in controlling rock weathering. Its properties, occurrence state, and migration characteristics within the rock mass have a significant impact on the weathering process. The effect of water on weathering can be divided into two pathways: physical and chemical. Both often occur simultaneously and superimpose on each other: physically, it manifests as alternation of dry and wet conditions and frost heaving and thaw subsidence; chemically, it is manifested as dissolution, hydration, and hydrolysis. The sand grains carried by water flow can also cause mechanical erosion of the rock mass, and the acidity and alkalinity of water as well as the ions it contains can either promote or inhibit chemical weathering to a certain extent.

According to the occurrence state, water in the rock mass can be classified into types such as

gaseous water, bound water, capillary water, gravitational water, solid water, and mineral water. When the temperature drops below the freezing point, the liquid water present in the pores freezes into solid water, causing a volume expansion of approximately 9% and generating frost heaving pressure on the surrounding rock walls, which leads to continuous expansion of the pores and eventually causes the rock mass to break. Gaseous water can migrate from areas of higher humidity to areas of lower humidity within fractures, and its chemical activity is usually higher than that of liquid water, making its impact on chemical weathering not to be ignored. Adsorbed water and film water are water films bound by the electrostatic attraction of particle surfaces, with small thickness and weak solubility, but they still participate in surface weathering.

Among all types of water, gravitational water that freely flows in pores and fractures plays a decisive role in the weathering process. Its movement channels within the rock mass are the pores and fractures of the rock, and the seepage law basically conforms to Darcy's law [9], gives:

$$Q = K\omega \frac{H_1 - H_2}{L} = K\omega \frac{dH}{dL} \quad (1)$$

In Eq.(1), Q is the seepage discharge, m³/s, K is the hydraulic conductivity, m/s, ω is the cross-sectional area of flow, m².

Table2. Classification of Rocks and Groundwater Hydraulic Conditions

Rock Classification		Porosity		Hydraulic conductivity/ (cm/s)					
		Void %	Fracture characteristics	10^2	10^0	10^{-2}	10^{-4}	10^{-6}	10^{-8}
Unconsolidated sediments	Gravel	30-40	—	—					
	Coarse sand	30-40	—		—	—	—		
	Fine sand	30-45	Sporadically developed		—	—	—		
	Silt	40-50	Poorly developed			—	—		
Consolidated rock	Limestone	1-50	Dissolution Joints		—	—	—	—	—
	Coarse sandstone	<20	Joints		—	—	—		
	Fine sandstone	<10	Joints			—	—	—	
	Mudstone	—	Joints						

The movement of gravitational water in rock masses is mainly controlled by factors such as water head height, rock layer thickness, rock fragmentation degree, and the dynamic viscosity coefficient of water. The general rule is that the more fragmented the rock and the higher the water head, the greater the flow velocity; as the rock layer thickness increases, the flow velocity gradually decreases. Different rock types also affect the type and speed of weathering by altering the flow velocity of underground water , as shown in Table 2.

The groundwater flowing through the rock fissures dissolves some soluble minerals along the way, forming solutions containing certain concentrations of mineral ions. When the water flow conditions change, chemical reactions occur within the solution and precipitates are produced, or when the external environment such as temperature changes, the original minerals in the solution or newly formed minerals may precipitate out, adhere to the surface of the fissures and gradually form crystal clusters with a certain shape. The continuous growth of these crystal clusters will generate considerable crystallization pressure, causing the original fissures to expand and even triggering new fissures, thereby damaging the integrity of the rock mass. The crystallization pressure can be calculated as:

$$p = \frac{RT}{V_s'} \ln \frac{c}{c_s} \quad (2)$$

In Eq.(2), P is the crystallization pressure, V_S' is the molar volume of the crystal, c/c_S is the degree of supersaturation, c is the concentration of the crystallizing solution, and c_S is the concentration at which the solution becomes supersaturated. Based on the calculation formula for crystallization pressure, the calculated values of the common minerals' crystallization pressure at the condition that c/c_S equals to 2 can be obtained, as shown in Table 3. From Table 3, it can be seen that the crystallization of different minerals varies significantly. Among the common minerals, under the same conditions, the crystallization pressure of rock salt is the highest. It can be inferred that the crystallization pressure is also an important factor affecting the rock's disintegration under dry-wet alternating conditions. Under different temperature conditions, the crystallization pressure changes

significantly. The higher the temperature, the greater the crystallization pressure. Similarly, it can be inferred that the temperature conditions may, to some extent, affect the rock's disintegration through the crystallization pressure.

Table3. Calculation Value of Mineral Crystallization Pressure from the Results of Winkler

Crystallizing Salts	Density/ (g/mol)	Relative molecular mass	Molar volume	Crystallization pressure at 8 °C	Crystallization pressure at 50 °C
Anhydrite	2.96	136	46	335	393
Epsomite	1.68	246	147	105	125
Gypsum	2.32	127	56	282	334
Halite	2.17	59	28	554	654
Sodium carbonate heptahydrate	1.51	232	154	100	119
Mirabilite	1.46	322	220	72	83
Thenardite	2.68	142	53	292	345
Trona	2.25	124	55	280	333
Kieserite	2.45	138	57	272	324

3. Mechanism of Differential Weathering

Differential weathering causes the surface layer of the slope to continuously peel off, forming a large number of rock cavities within the soft rock layer, which subsequently leads to the collapse and instability of dangerous rock masses. This is a common geological disaster type in mountainous high and steep slopes. Based on field geological investigations and laboratory tests, combined with previous data, starting from aspects such as rock mineral composition, type and degree of cementation of cementing materials, macroscopic and microscopic structures, and temperature effects, it analyzes the formation mechanism of differential weathering, with the aim of providing a basis for in-depth understanding of the differential weathering process and the development of slope protection and control measures.

3.1 Field Observation of Rocks and Laboratory Disintegration Experiments

3.1.1 Field observation

The brick-red mudstone and purple fine-sandstone mudstone are the most prone to weathering and disintegration in the field. The weathering and flaking of mudstone is essentially a process of water-induced disintegration after drying and contraction. Field observations show that after drying and losing water, the surface of the mudstone contracts, forming network-like contraction fissures which cut the rock mass into various-sized polyhedrons. When water again comes into contact, the mudstone absorbs water and expands, forming ellipsoidal-like weathered surfaces similar to spheres, and then gradually disintegrates under the action of rain erosion and wind erosion.

The disintegration of brick-red mudstone progresses gradually from the surface inward. The outermost layer has weathered into fine scales or small spheroids, while the fragment size increases toward the interior, with distinct weathering zonation. From the scaly weathered layer at the surface to the essentially unweathered core at depth, the zonation is clear, and the significant depth of disintegration is about 15 cm. The purple silty mudstone shows a similar weathering pattern, but the overall degree of weathering is weaker. A distinct zonation can also be observed from the outside inward: the surface layer is thoroughly weathered into fine scaly and spheroidal particles, and the fragment size increases gradually toward the core.

3.1.2 Laboratory disintegration test

The five rock samples were air-dried at room temperature and placed separately in five beakers, which were then filled with clean water until the samples were fully submerged. The disintegration process during water immersion was observed, as can be seen from Figure 1.

The purple silty mudstone, dark purple argillaceous siltstone and brick-red mudstone were ground and sieved to obtain particles smaller than 0.25 mm for particle size analysis. The cumulative grading curves of the three samples are shown in Figure 2.

In Figure 2, Series 1, 2, and 3 represent purple-red sandy mudstone, dark purple muddy sandstone, and brick-red mudstone respectively. Through analysis, it is known that the percentage of clay particles in the brick-red mudstone is the highest, while the clay particle content in the dark purple muddy sandstone is

the lowest, and the purple sandy mudstone is in the middle. Through rock disintegration experiments, it is found that the water immersion disintegration properties of the three rocks also decrease in the order of brick-red mudstone, purple-red sandy mudstone, and dark purple-red muddy rock. Based on this, it can be inferred that the disintegration property of the rock is related to the content of clay particles it contains.

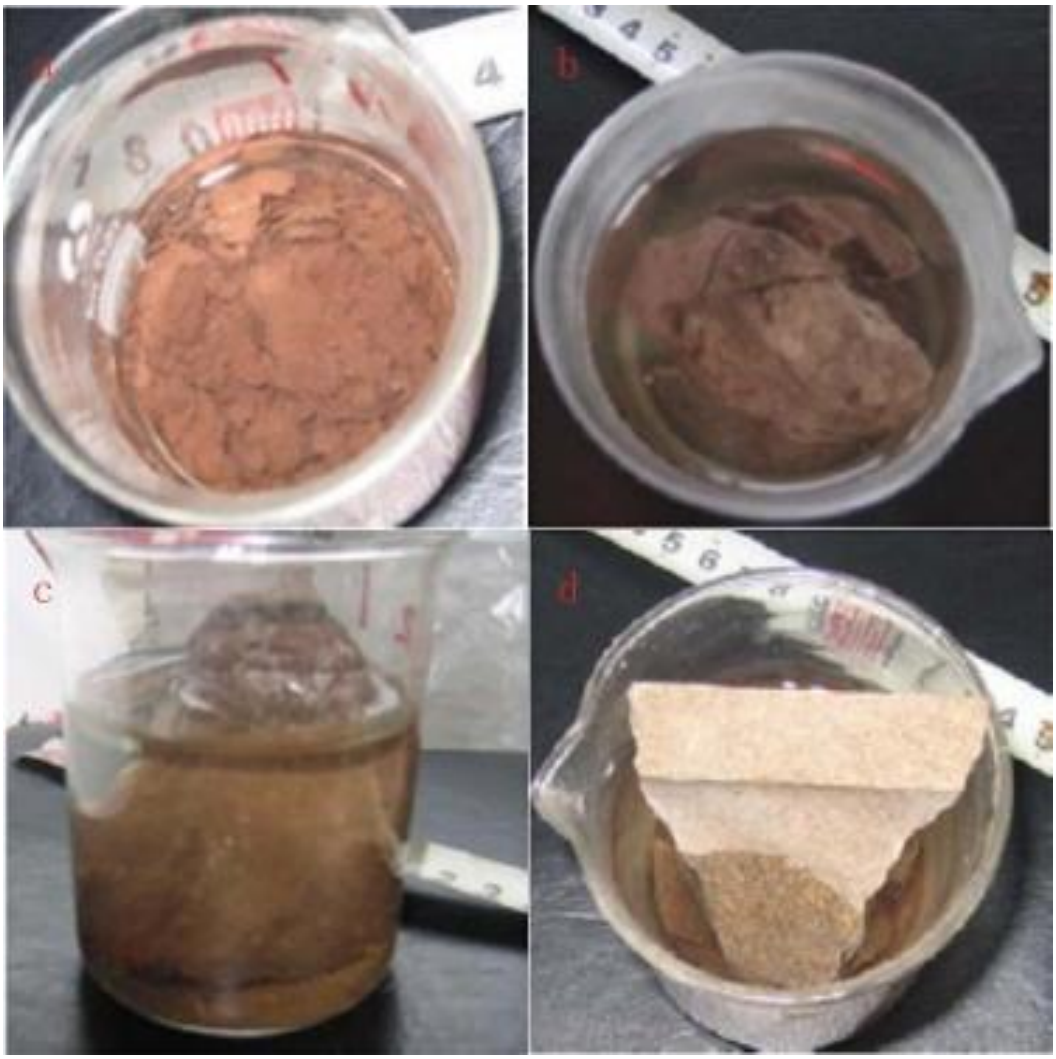


Figure 1. Rock Specimens after the Disintegration Test: (a) Brick-Red Mudstone; (b) Purple Silty Mudstone; (c) Dark Purple Argillaceous Siltstone; (d) Gray-White Feldspathic Quartz Sandstone.

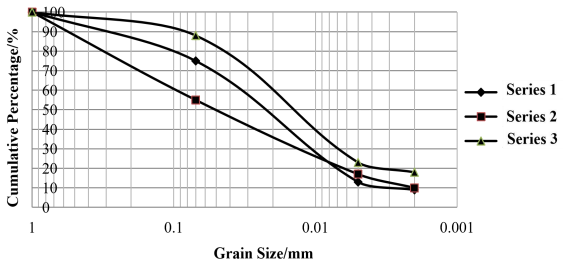


Figure 2. Particle Size Distribution Curves of Mudstone (Sandstone).

3.2 Clay Mineral Content and Differential Weathering of Rocks

Clay minerals are the main mineral components of clay particles. Thus, the experimental conclusion in Section 3.1 can be understood as follows: the disintegration property of rocks is closely related to the content of clay minerals. As previously discussed when discussing the influencing factors of differential weathering, clay minerals mainly include kaolinite, illite, and montmorillonite, and they are the intrinsic factors that control the deformation and strength properties of rocks, especially the disintegration and expansion properties. Among them, montmorillonite plays a controlling role in the water properties of rocks due to its special structure, large specific surface area, and weak interlayer bonding force. Based on this, this section analyzes the mechanism of the influence

of montmorillonite on differential weathering.

The clay minerals in rocks can be produced in the form of single minerals or exist in the form of mixed-layer minerals. In the experiment, the total amount of clay minerals was first determined by X-ray diffraction, and the relative content of montmorillonite was calculated. Then, the content of montmorillonite was precisely determined by the methylene blue method (S_nCl_2 titration method). The two methods were mutually verified, and the final results are listed in Table 4.

Table 4. Disintegration Characteristics, Specific Surface Area and Montmorillonite Content of Rock Samples.

Rock types	Disintegration upon water immersion	Montmorillonite percentage (%)	Specific Surface Area (m^2/g)
Brick-red mudstone	Disintegrates into scaly fragments and mud-like powder	7.85	98.72
Purple-red sandy mudstone	Partially cracks into scales or mud-like powder	4.72	86.74
Dark purple muddy sandstone	Cracks into small blocks with debris spalling	3.65	75.58

As shown in Table 4, the montmorillonite content in rocks is positively correlated with both the specific surface area and the disintegration behavior upon water immersion: the higher the montmorillonite content, the larger the specific surface area, and the more readily the rock disintegrates after immersion.

3.3 Cementation and Differential Weathering

3.3.1 Determination of cement composition and content

Cementation is the diagenetic process by which loose clastic particles are bound together by cement, and it exerts a controlling effect on the engineering properties of rock. According to the type of cement, cementation can be divided into inorganic and organic types; the former includes siliceous, ferruginous, calcareous and anhydrite cementation. Different rocks vary considerably in cement type and degree, and these features often change gradually. The strength of cementation depends not only on the composition, content and occurrence of the cement, but also on the activity of the clay minerals being bound: kaolinite and illite are relatively inactive and easy to cement, whereas montmorillonite is highly active and more difficult to cement. The composition and content of cement in representative rocks were determined by XRD and chemical analysis; the results are listed in Table 5.

Table 5. Cement Composition and Content.

Rock specimens	Cementation				Montmorillonite (%)
	$CaCO_3$	SiO_2	Fe_2O_3	Al_2O_3	—
Gray-white feldspathic quartz sandstone	7.32	—	—	—	—
Blue-gray calcareous feldspathic sandstone	14.26	—	—	—	—
Dark purple muddy sandstone	1.27	0.13	0.75	0.18	3.22
Purple-red sandy mudstone	2.36	0.11	0.92	0.25	4.45
Brick-red mudstone	7.99	0.14	1.02	0.19	8.53

The test results show that, among the cements of the five rock samples, only the $CaCO_3$ content varies considerably, while the other components are roughly similar. The blue-gray calcareous feldspathic sandstone has the highest $CaCO_3$ content; nevertheless, it disintegrates more readily than the gray-white feldspathic quartz sandstone. It can therefore be inferred that calcareous cementation is not a high-strength cementation type.

3.3.2 Analysis of cementation degree

Some scholars proposed the diagenetic cementation parameter (GCP) to evaluate the cementation degree of rocks. This parameter is defined as the ratio of the dry saturated water absorption of rock powder (<0.25mm), with the original fabric completely destroyed) to that of an intact sample retaining the original rock fabric. It comprehensively reflects the cementation degree, material composition and physicochemical properties of the rock. A higher GCP indicates stronger cementation, and accordingly better durability and weathering resistance. According to the GCP value, the cementation degree of rocks can be classified into four grades, as shown in Table 6.

Table 6. Classification of Cementation Degree of Rocks.

Cementation degree	GCP	Disintegration behavior upon water immersion
Weakly cemented	1～2	Strongly absorbs water upon immersion and disintegrates into mud, losing strength
Moderately cemented	2～5	Disintegrates into debris and fragments upon immersion
Strongly cemented	5～10	Cracks upon immersion or fails in a fragmentary manner
Extremely strongly cemented	>10	No failure upon immersion, or cracks only along fractures; strength reduction is insignificant

The cementation degree of rock samples were quantitatively evaluated according to the above grading criteria, as listed in Table 7.

Table 7. Cementation Degree of Rock Samples.

Rock specimens	Dry saturated water absorption		Cementation coefficient	Cementation degree
	Rock block	Rock powder		
Gray-white feldspathic quartz sandstone	1.89	19.03	9.76	—
Blue-gray calcareous feldspathic sandstone	4.76	25.44	5.25	—
Dark purple muddy sandstone	4.33	22.09	4.62	3.36
Purple-red sandy mudstone	5.28	22.36	4.52	4.49
Brick-red mudstone	28.38	28.77	1.17	8.13

As shown in Table 7, the cementation degree is negatively correlated with the disintegration behavior upon water immersion: the smaller the GCP, the more readily the sample disintegrates after immersion.

3.4 Rock Mass Structure and Differential Weathering

Rock mass structure can be classified into massive, layered, cataclastic and dispersed structures, with the spacing between structural planes and the integrity coefficient decreasing in turn [10]. According to origin, structural planes are divided into primary, tectonic and supergenic types. Consistent with the discussion of factors influencing differential weathering in previous analysis, the structural planes closely related to differential weathering mainly include three types: joints and fractures in hard rocks, fractures generated in soft rocks under wet-dry cycles, and primary structural planes such as bedding. The influence of rock mass structure on differential weathering is exerted mainly through its control over the migration pathways of water flow and wind.

3.4.1 Structural planes in hard rocks

Structural planes in hard rocks are well connected and provide favorable pathways for groundwater flow, which plays an important role in rock weathering. Analysis of groundwater action across the four structural types shows that, from massive and layered to cataclastic and dispersed structures, groundwater action intensifies in turn, while the weathering resistance of the rock mass decreases accordingly.

3.4.2 Fractures in soft rocks

Taking the interbedded soft-hard rock strata as an example, mudstone has low permeability and can hardly form continuous seepage pathways; it thus acts as a barrier to fractures in adjacent hard layers, suppressing weathering from propagating to depth to some extent. However, soft rocks exhibit pronounced swelling-shrinkage behavior. Under wet-dry cycles induced by groundwater or rainfall, weathering disintegration accelerates: cracks develop on the surface of dried mudstone and propagate inward; upon re-wetting, these cracks absorb water and expand, leading to scaly spalling. Where a free face is present, soft rock continues to spall and recedes inward, forming rock cavities. Under overlying load, the soft layer may undergo plastic-flow squeezing, causing the rock mass to fracture and lose stability, with structural planes extending further and weathering intensifying accordingly.

3.4.3 Primary structural planes in soft rocks

Field observations and laboratory tests show that, during drying shrinkage and water-immersion disintegration, mudstone first cracks into small blocks and then spalls along the surface in scaly sheets of roughly uniform thickness. The scaly disintegration planes may be either parallel or perpendicular to the bedding, and their orientation follows the external shape of the rock block rather than the mudstone bedding. In contrast, cracks induced

by drying shrinkage are essentially perpendicular to the rock block surface (Figure 3). This indicates that neither drying-shrinkage cracks nor immersion-disintegration planes develop along the maximum principal stress direction established during diagenesis. The likely reason is that repeated drying shrinkage and wetting disintegration have damaged the mesostructure of the rock, reducing the bond strength between bedding layers until the swelling pressure generated upon water uptake exceeds that bond strength.



Figure 3. Mudstone Disintegration Plane Upon Water Immersion

3.5Temperature and Differential Weathering

It is generally believed that rocks subjected to severe temperature fluctuations develop fractures due to thermal expansion and contraction, with consequent strength reduction and accelerated weathering. To verify the relationship between temperature and differential weathering, the following test was conducted: air-dried representative samples were heated in an oven to 80℃ and held isothermally for 12h, then removed and kept at room temperature for 12 h; this cycle was repeated for 7 days. After the test, all samples remained essentially unchanged, with no obvious new fractures. It can thus be inferred that short-term temperature variation itself has little direct effect on rock weathering, and that the influence of temperature on weathering is largely exerted indirectly through water. As for the effect of temperature on the weathering of saturated rocks, it remains difficult to control experimentally and warrants further study.

4.Numerical Simulation of Differential Weathering in High-Cut Slopes

Under differential weathering, the soft rock interbedded between hard layers spalls and forms deep rock cavities. As the cavities develop, the initial stress state within the high-cut slope changes, leading to stress redistribution and stress concentration, while deformation varies accordingly across the rock mass. To understand the deformation and failure mechanism of high-cut slopes and objectively evaluate their stability, the FLAC^{3D} numerical method [11-13] is used in this chapter to simulate the stress field and rock mass deformation of the slope.

Two materials are used in the calculation, with parameters listed in Table 8. The Mohr-Coulomb elasto-plastic constitutive model is adopted. The computational domain is 20 m wide and 30 m high; the lateral boundaries are fixed in the horizontal direction and the base is fixed in the vertical direction, based on which the numerical model is established.

Table 8. Parameters for Numerical Simulatio.

Rock types	Density (Kg/m^3)	Elastic modulus (Gpa)	Possion's ratio	Cohesion (Gpa)	Internal friction angle
Gray-white feldspathic quartz sandstone	2480	10	0.2	0.2	35
Brick-red mudstone	2560	5	0.4	0.25	39

Figure 4 shows the vertical and horizontal displacement contours of the slope before and after cavity formation. It can be seen that the displacement field changes significantly after cavity development.

The comparison between Fig. 4(a) and Fig. 4(b) shows that: before cavity formation, the vertical displacement in the slope is all negative and increases gradually from bottom to top, indicating upward accumulation of compressive settlement; after cavity formation, the displacement increases from the surrounding

rock toward the free face of the cavity — downward settlement dominates at the cavity roof, while positive values appear at the cavity floor, i.e., rebound toward the free face, with settlement and rebound roughly symmetric about the cavity. The displacement of the cantilevered rock mass results from the combined action of gravity and unloading rebound, and may appear either as downward settlement or upward rebound. The comparison between Fig. 4(c) and Fig. 4(d) shows that: before cavity formation, the horizontal displacement increases toward the free face, and the displacement at the soft-rock free face is larger than that at the hard-rock free face; after cavity formation, the horizontal displacement inside the cavity decreases, while that outside the cavity points inward toward the free face, which is attributed to unloading rebound following the spalling of soft rock.

Figure 6 shows the maximum and minimum principal stress contours of the slope after cavity formation. The stress state around the cavity is noticeably modified.

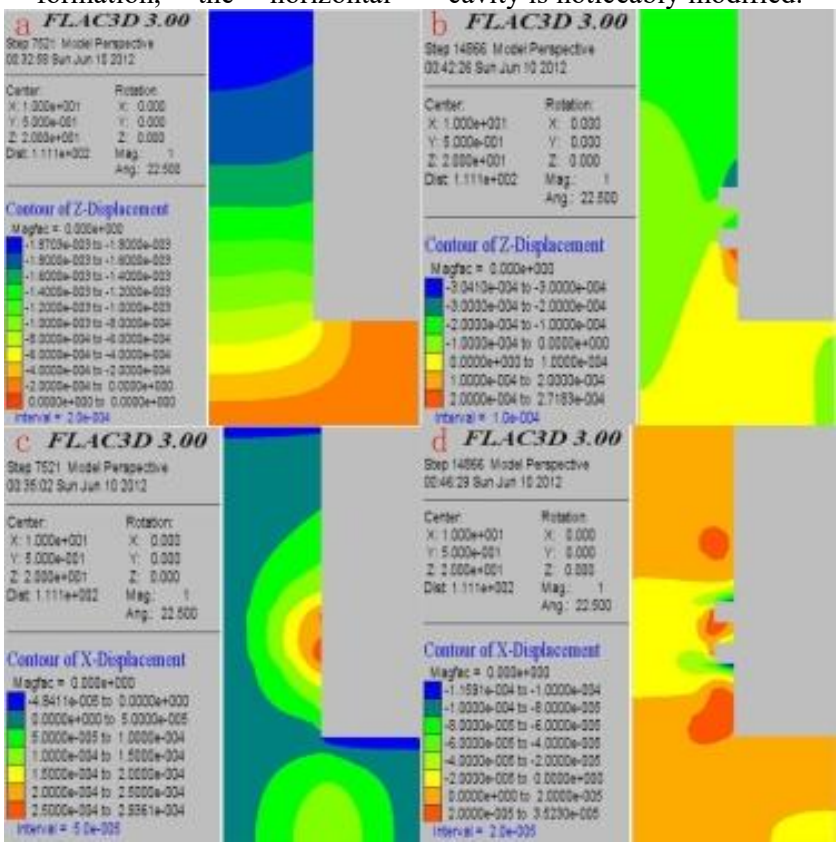


Figure 4. Displacement Contours of the Slope: (a)Vertical Displacement before Cavity Development; (b)Vertical Displacement after Cavity Development; (c)Horizontal Displacement before Cavity Development; (d)Horizontal Displacement after Cavity Development

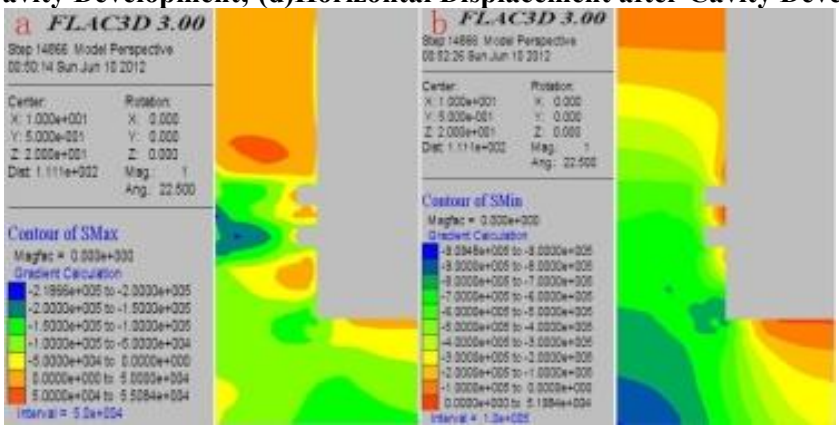


Figure 5. Stress Contours of Slope: (a) Maximum Principal Stress; (b) Minimum Principal Stress

As can be seen from Fig.5(a), the maximum principal stress approaches zero near both the slope free face and the cavity free face; tensile stress concentration occurs locally on the exposed surface of the hard layer inside the cavity. Fig.5(b) shows concentration of the minimum principal stress in the cantilevered rock mass and locally along the slope free face. Toward the interior of the slope, both the maximum and minimum principal stresses gradually recover to the in-situ stress level.

The FLAC^{3D} simulation compares the displacement and stress fields of the slope before and after cavity development. The results indicate that, once the cavity forms, the probability of instability and subsequent collapse in the surrounding rock mass increases considerably.

5. Conclusion

Based on the review of domestic and overseas research on differential weathering, and combining theoretical analysis with field investigation, this study takes the Wanzhou area in the Three Gorges Reservoir region as the study area. Representative rock samples were selected through regional geological survey for detailed field examination and laboratory testing, leading to the following main conclusions:

(1) The high-cut slopes in the Wanzhou section of the Three Gorges Reservoir area are dominated by interbedded soft–hard sandstone and mudstone of Jurassic inland shallow-lacustrine deposits. Differential weathering is a key factor responsible for the development of dangerous rock masses and frequent collapse hazards in this area. The collapse modes can be classified into four types: weak-base type, sliding type, toppling type and faulting type.

(2)Differential weathering is jointly controlled by multiple factors including mineral composition, rock mass structure and tectonics, topography, climate and water. Water participates in the alteration of mineral composition; rock mass structure governs groundwater migration; and topography determines the occurrence state of water. The coupled action of these factors governs the progress of differential weathering.

(3)Slake durability tests and measurements of mineral composition and cementation show that the mineral composition and structure of rocks exert a controlling effect on weathering, among which the clay mineral content (especially montmorillonite content) is the intrinsic factor governing differential weathering. The mesostructural characteristics revealed by scanning electron microscopy (SEM) provide an intuitive basis for understanding the weathering behavior of rocks.

(4)FLAC^{3D} numerical simulation indicates that, after rock cavities develop due to differential weathering, the stress field and displacement field of the slope are significantly modified, and the probability of instability and subsequent collapse in the rock mass around the cavities increases markedly.

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