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Characterization of soil composition and calculation of genetic mechanism in the landslide zone of Liujiabao landslide in Three Gorges reservoir area

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ABSTRACT

The Three Gorges Reservoir Area is a hotspot for landslide disasters, with many landslide development patterns and influencing factors remaining unclear. The slip zone soil, a weak interlayer between the sliding mass and the bedrock, has inherently low strength, which is a critical factor in landslide occurrence. Water is one of the most active elements reducing the shear strength during the formation of the slip zone. Given the particularity of reservoir bank water-related landslides, the mineral composition and geochemical characteristics of the slip zone and its surrounding rocks and soils exhibit significant variations across different geological periods and environments. These changes reveal the mechanisms and extent of water-rock interactions, further clarifying the fundamental reasons for the reduction in shear strength of the slip zone. The results show that in the Liujiaobao landslide in Quchi Township, Wushan County, Chongqing, within the Three Gorges Reservoir area, the composition of minerals and the content of major chemical elements in the slip zone soil and its surrounding rocks and soils indicate that the slip zone and surrounding rocks and soils form the material basis for the slip zone. During its formation, the groundwater in the slip zone is closely connected with external hydraulic forces, continuously influenced by groundwater, leading to changes in the physical properties of the rock and soil mass. This is accompanied by the hydrolytic mudification of marl debris, dissolution of calcite, and interconversion among clay minerals, which are the main reasons for the attenuation of the shear strength of the slip zone soil.

Keywords: Slip zone soil, mineral composition, characteristic geochemical components, water-rock interaction mechanisms, physical mechanical property

1. Introduction

The Three Gorges Project is a large-scale and world-renowned project with great comprehensive

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benefits in flood control, power generation and navigation, and is the backbone project for the development and management of the Yangtze River [1-2]. The construction of the Three Gorges Project will have a wide and far-reaching impact on the ecology and environment, it can effectively control the upstream flood, cut down the flood flow in the middle reaches of the area, improve the flood control capacity, prevent destructive disasters from occurring on both sides of the Jingjiang River, reduce the loss of floods in the middle and lower reaches of the plains and safeguard the people's lives and properties, and participate in the west-east power supply and provide clean energy [3-6]. The construction of the Three Gorges Project can really realize the development of water conservancy, eliminate water damage, develop and utilize water resources, protect the environment, benefit the people and promote the sustainable development of the Yangtze River Basin.

Since the mid-twentieth century, with the large-scale development of social economy, the gradual expansion of the spatial scope of human activities, the intensification of the disturbance of major engineering activities and extreme natural activities to the geological environment, and the influence of global extreme climate change, the frequency and intensity of landslide events have increased, and the casualties and economic losses caused by landslides have also increased [7-10]. The geological conditions of the Three Gorges Reservoir area of the Yangtze River are complex, human engineering activities are strong, and geological disasters such as landslides are widely developed and occur frequently, which is a phenomenon of instability, sliding, or collapse of the slope near the reservoir area under certain conditions, which not only threatens the operation of the Three Gorges Reservoir and the safety of local people's lives and property, but also has a serious impact on the downstream ecological environment, directly or indirectly affecting the economic development and social stability of the region [11-14].

Because the landslide lot in Three Gorges reservoir area is mainly composed of residual slope accumulation layer, landslide accumulation and artificial filling of the loose layer of the fourth system, the accumulation layer is thick and contains a lot of loose soil, the strength is very low, which belongs to the easy to slip stratum [15-16]. And the Three Gorges reservoir area in the Yangtze River system, the water level changes every year, by the seepage pressure, so that the landslide body repeatedly in the water immersion, resulting in the effect of instability, the result is not only to increase the slope weight, but also play a softening effect on the soil, reducing the shear strength of the soil body [17-20]. Therefore, the study of landslide disaster risk in the Three Gorges reservoir area, as well as the changes and trends of landslide disaster risk under the permeability properties and compositional characteristics of the soil under the water level changes in the region, is a major and urgent need to realize the disaster prevention and mitigation strategy in the reservoir area and to ensure the normal operation of the reservoir, and has very important scientific and practical significance.

At present, most scholars have already studied the landslide events around the Three Gorges Reservoir Area, and in the research direction, they are mainly divided into landslide formation mechanism, damage mode, stability influence, landslide type classification, susceptibility and so on. Literature [21] summarized that the deformation characteristics of geological disasters in the Three Gorges Reservoir Area are mainly of oscillatory, linear, and step type, and the step type landslide displacement is the main deformation characteristic. Literature [22] explored the landslide motion characteristics of Tanjia River in Three Gorges Reservoir Area through field research, reservoir water level monitoring, and surface displacement monitoring, presenting load-damaged landslide step-type displacement, and the motion speed presenting fast-rise-fast-fall-slow-fall, while the landslide deformation was simulated by using the discrete element system, MatDEM, in order to predict the possible hazards. Due to the wide distribution of the Three Gorges Reservoir area, most of the researchers have studied the area as a region. Literature [23] conducted a comprehensive formation mechanism study of Gongjiacun landslide in the Three Gorges reservoir area, the landslide was stable in natural state and heavy rainfall environment, but the leading edge heavy load and slope fluctuation secondary landslide rate increased, and the risk of landslides increased under heavy rainfall or continuous rainfall attack, meanwhile, the falling of the water level increased the superporous hydraulic force of the soil in the slope zone, which reduced the stability of the slope. Literature [24] calculated the water level fluctuation and rainfall in Maliulin in Three Gorges reservoir area by two models, Morgenstern-Price and Monte Carlo, and the landslide stability showed the same trend with the water level change in the annual cycle. Literature [25] explored that 90% of the identified landslides occurred at the slope corners and 80% occurred below 600 m above sea level by constructing a landslide database and distribution map of the Zigui Basin in the Three Gorges Reservoir Area, and the water level of the reservoir of 145-155 m greatly threatened the stability of the slopes.

Most of the landslide studies in a place in the Three Gorges Reservoir Area are carried out through monitoring techniques for long-term data acquisition and analysis. Literature [26] carried out long-term monitoring of the Ganjingzi landslide in the Three Gorges Reservoir Area through detection techniques for a long period of time, and explored that the landslide evolution in this place mainly went through three periods, namely, the stabilization period before the reservoir impoundment, the initial period of the movement degradation and destruction and the gradual acceleration period, and the latter two periods are the susceptibility to the water level of the reservoir and will be in the. Referring to the susceptibility, literature [27] analyzed the susceptibility of landslides in the Three Gorges Reservoir area using several machine learning models, and the five levels of susceptibility influencing factors are topographic features, geological activities, ecological environment, meteorological changes, and human engineering, which have been supported by the vector machine model to assess the best in real time. In addition, literature [28] mitigated landslide deformation to a certain extent by installing stabilizing landslide piles and monitoring system, but the resistance effect of the piles gradually weakened with the increase in age, reservoir drop, and will be in the cycle. Similarly, literature [29] investigated the deformation characteristics and mechanism of Wosha Creek landslide through the monitoring data and geological investigation at the early stage of water storage in Three Gorges Reservoir area, and at the same time, combined with the water level of the reservoir and rainfall, explored the evolution of its landslide stability. Literature [30] calculated the landslide deformation mechanism in the Three Gorges reservoir area using FLAC3D, the initial water storage stage, the landslide stability gradually decreases, the decline of the reservoir water level directly promotes the occurrence of landslides, and on the contrary the rise of the water level, landslides will not happen to a certain extent, but this effect is limited.

There are numerous classifications of landslides in the Three Gorges reservoir area, but there is no fixed standard for landslide classification. Literature [31] proposed a set of classification criteria based on a case study to compare and analyze the cumulative displacement curves, sliding body permeability parameters, and sliding surfaces of seepage-driven and buoyancy-driven types of reservoir landslides in the Three Gorges reservoir area. Among them, dynamic pressure landslide is the type of landslide that is more affected by the water level, literature [32] constructed a dynamic water pressure landslide model to explore the mechanism of change of this landslide type, the leading edge and the back of the landslide are deformed at the same time, and the back of the landslide is predominantly deformed by tensile deformation, which is due to the low intrinsic permeability coefficient of the sliding body on one hand, and the decline of the water level of the reservoir on the other hand. The sudden porosity and permeability coefficient are interrelated and influence the landslide deformation process. Literature [33] concluded that the large variability of the permeability of landslide soils in the Three Gorges Reservoir area and the permeability changes were influenced by pipe network seepage, interface network seepage and pore water seepage, which laterally highlights the complexity of the hydraulic characteristics of landslides. Literature [34] produced a new type of seepage device for slip zone soil, and at the same time conducted ring shear test to reveal the mechanism of residual strength reduction of slip zone soil and the weakening law of mechanical strength of slip zone soil in Tongjia landslide in Three Gorges reservoir area. Literature [35] analyzed that under the large deformation environment of the Three Gorges Reservoir Area Outang slip belt soil significantly softened, the residual strength is stable, and the constructed mechanical model reflects the large displacement shear mechanical properties of the slip belt soil, and with the increase of this displacement, the stability decreases until it is constant. Literature [36] conducted creep tests on the debris soil produced during the recovery period of slow-moving landslides in the Three Gorges Reservoir Area, explaining the deformation pattern mechanism of step landslides.

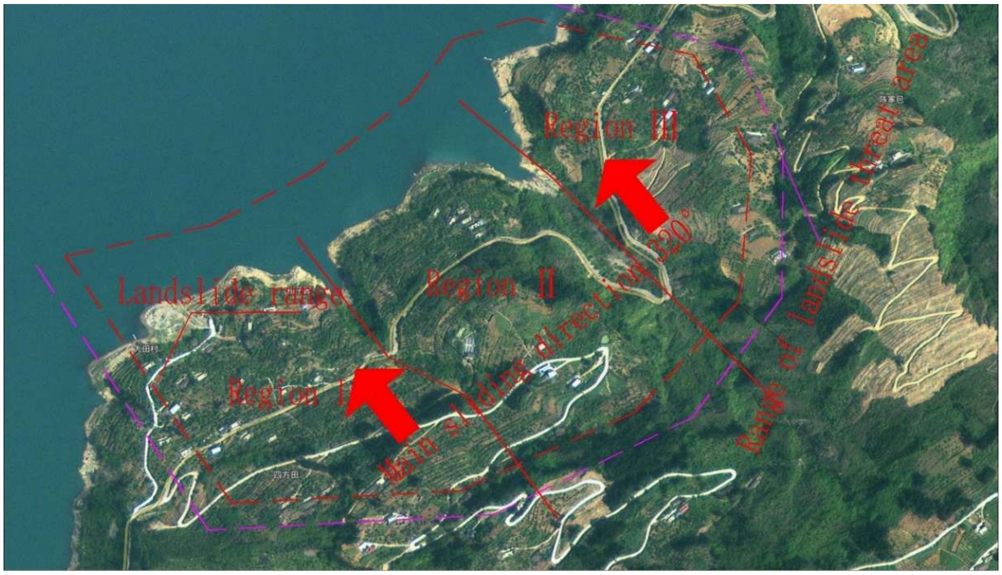
In summary, the study shows that the change of water level in the reservoir is the main factor affecting the landslide, and the rise of water level has less influence on the occurrence of landslides, and vice versa has a great influence. Changes in the permeability parameters of the sliding body affect the hydraulic characteristics of the landslide, but the specific mechanism of the impact is not clear, at the same time, the inherent factor in the mechanism of change of the landslide is a low coefficient of permeability, the mechanism of residual strength of the slip belt soil and the permeability of the soil have been done research. However, there are large differences in soil properties in different regions, and the existing studies are very few for the characteristics and genetic mechanism of soil in the landslide zone of the Three Gorges Reservoir Area. Therefore, this paper investigates the characteristics and genetic mechanism of the soil in the landslide zone of Liu Jiabao landslide in the Three Gorges Reservoir Area, and the research results can provide scientific basis for the engineering design and disaster prevention and mitigation in the Three Gorges Reservoir Area, and at the same time, provide useful reference for the research of similar engineering geological problems.

Therefore, there are significant differences in mineral composition, chemical composition, structural characteristics and physical and mechanical properties of slip zone soil under various geological conditions, and analysis of it can reveal its genesis and evolution process in a certain sense. This paper takes Liujiabao landslide in Quchi Township, Wushan County, Chongqing City, Three Gorges Reservoir Area as the research object. Most of the studies in this area focus on the mechanical properties of landslides, and a few study on geochemistry. Therefore, this paper discusses a series of influences of mineral composition and geochemical composition of such slip zone soil and groundwater on the formation process of slip zone soil. Combined with the results of mechanical tests, the physical properties and structural changes of rock and soil mass in the process of landslide formation are further clarified. Due to the complex characteristics of slip zone soil itself, the current research on slip zone soil still needs to be expanded. In this paper, the actual engineering situation is investigated on site, and the physical properties of rock and soil mass are combined with the use of geochemical methods to study the slip zone soil. And predicted the next activity trend of landslip. The research results can further reveal the basic conditions of the formation of this kind of slip zone soil and the causes of the changes of characteristic geochemical components, which can provide a basis for the scientific prevention and control of landslide geological disasters.

2. Geological Background

2.1. *Landslide overview*

As shown in Figure 1, Liujiabao landslide, which is fording landslide, located in Yueming Village, Quchi Township, Wushan County, on the right bank of the Yangtze River, belongs to the Daxi-Sanxi low mountain and hilly landform, and the microlandform of the slope is dominated by gentle slope, platform and steep slope. The terrain is high in the southeast and low in the northwest. The landslide plane is “round-backed armchair” and the profile is “concave”. The longitudinal length of the landslide is about 600m, the transverse width is 1050m, the height of the potential shear outlet of the front is about 90m, the height of the rear wall is up to 340m, and the height difference is about 250m. The area is about 52.1×104m^2, the average thickness of the sliding mass is 55m, the total volume is about 2865×104m^3, and the main sliding direction is 320°, which belongs to extra-large soil landslide.



(a) Schematic diagram of the extent of the landslide

(b) Landslide trailing edge gully map (c) Disaster area scene map

Fig. 1. Landslide range diagram and local scene map

2.2. Stratigraphic lithology

The exposed strata in the landslide area from new to old are: Quaternary artificial fill layer (Q_4^{ml}), Quaternary landslide accumulation layer (Q_4^{del}), and the fourth member of the Middle Triassic Badong Formation (T_2b^4).

See Figure 2, Accumulation horizon landslide, which is distributed in the whole landslide, presents gray, yellow brown, gray black, mainly medium dense with local slightly dense. The land surface 0-2m is mainly silty clay, the crushed mother rock is mainly gray-dark gray marl, occasionally a small amount of sandstone gravel. Below land surface, it is mainly broken stone with silty clay, and the local can be defined crushed stone soil. Broken stone mother rock is mainly gray-dark gray marl, followed by gray-gray white sandstone, and occasionally purplish red mudstone. The stratigraphic lithology of the fourth member of the Middle Triassic Badong Formation is mainly light gray and gray-green marl, and partially contains purplish red and light gray medium-thick mudstone, and partially contains thin layers of purplish red silty mudstone and sandy mudstone.

Fig. 2. Marl of the fourth member of the Middle Triassic Badong Formation

2.3. Geological structure

Wushan County is located in the upper Yangtze gap platform of the Yangtze paraplatform. In Geographical, Wushan County is at the intersection point of uplift fold belt of the Dabashan Arc, the eastern Sichuan fold belt and the Sichuan-Hubei Hunan-Guizhou, which is an important component of the third uplift belt of the neocathaysian structural system, and has quite complex geological structure. The structural features here are mainly folds, and a series of parallel North-East to South-West trending anticlines and synclines occur alternately. Notable large structures include Qiyaoshan anticline, Wushan syncline, Hengshixi anticline and Guandu syncline. In the north of the temple, anticlines and synclines are roughly equal in width, and anticlines are mostly box-shaped, while the drawer syncline with a narrow or flat bottom is alternately arranged, forming a unique folding structure of slot. The fractures are not well developed, mainly distributed in the Dengjia complex anticlinal structure area. In general, the fractures are small in scale, the joints and fissures are developed, and the structural stress can change the rock and soil structure.

The landslide is located in the southeast wing of Wushan syncline, affected by secondary tectonic action, the rock strata are broken, and the cracks are filled with silty clay. The rock strata occurrence is 286°-345°∠28°-46°, and the plane bonding is poor. There are three main groups of structural cracks:

1) Fissure 1 occurs at 168°∠72°, the opening degree is about 1 ~ 3cm, the extension length is about 2 ~ 6m, the spacing is 0.5-1.5m, the fracture surface is straight and there is no filling.

2) Fissure 2 occurs at 305°∠81°, the opening is about 1-3cm, the extension length is 2-3m, the spacing is 0.5-1.5m, the crack surface is straight, and the local silty clay is filled.

3) Fissure 3 occurs at 26°∠86°, the extension length is 3-20m, the spacing is 0.2-1.5m, the opening is 0.5-2cm, and the fissure combination degree is poor.

The structural outline map of Wushan County is as Figure 3:

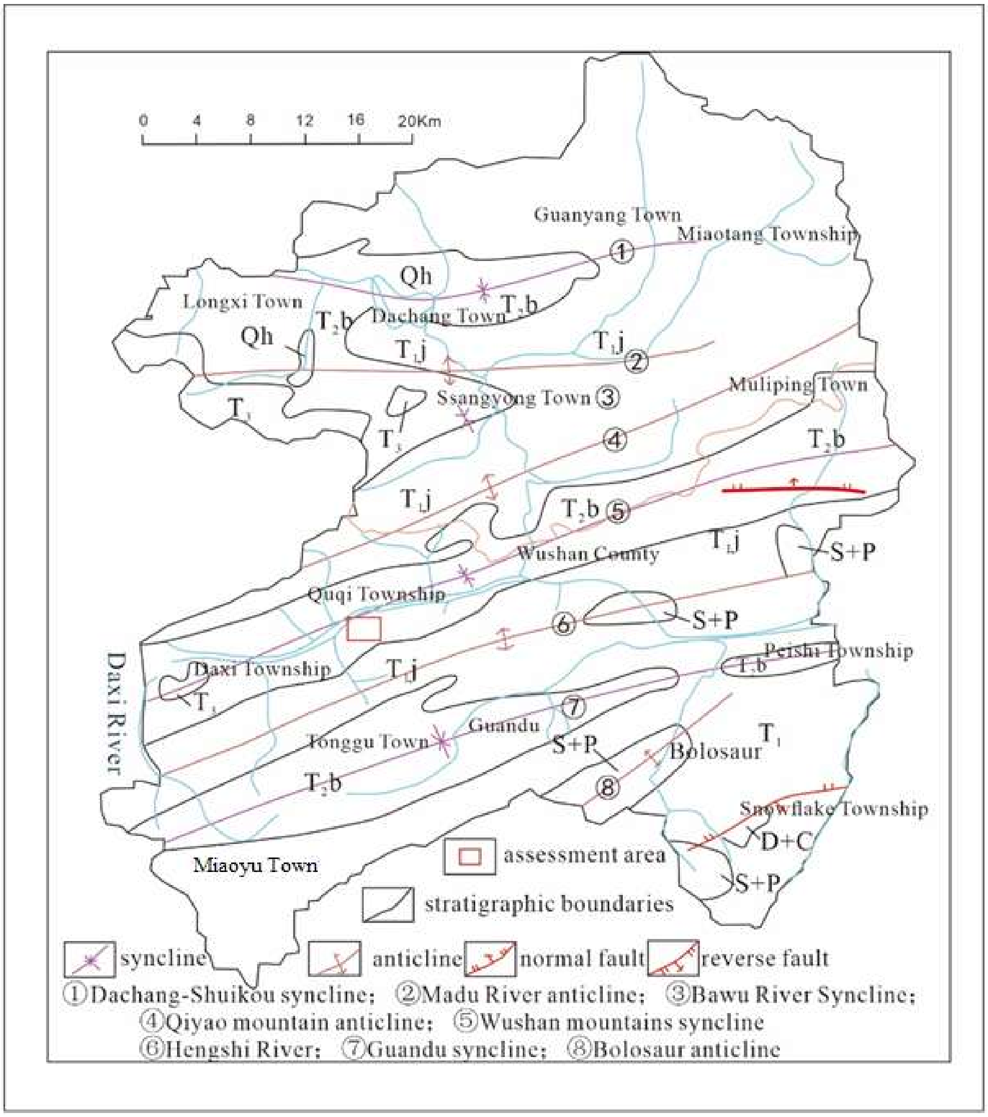


Fig. 3. Outline of the structure of the exploration area

2.4. *Hydrogeological condition*

Liujiabao landslide is located in the mountain slope area, which is a ladder form of "steep slope-gentle slope-steep slope-gentle slope" from top to bottom, and is washed and cut by atmospheric rainfall and surface water runoff.

According to its distribution characteristics, the groundwater in this area can be divided into two types: pore water in loose soil layer and bedrock fissure water. The groundwater in this area is mainly composed of precipitation and domestic water used by surrounding residents, which drains down the slope and enters the Yangtze River. During the period of water rise, as the water level rises and the surface water level exceeds the depth of groundwater buried along the river bank, the groundwater below the river bank is permeated and replenished, the groundwater on the slope continues to rise with the rise of the river. And followed the water level of the Yangtze River changes, the connection between groundwater and the ground water is also changed.

3. Spatial Structure Characteristics of Landslide

3.1. *Sliding mass characteristics*

Through geological drilling, it can be seen that the sliding mass is mainly composed of gravel soil and silty clay (see Figure 4). The surface of the sliding mass 0-2m is mostly composed of silty clay with gravel, and the local thickness can reach 5m, which is mainly yellow brown. The gravel mother rock is mainly gray-dark gray marl, occasionally a small amount of sandstone gravel, the gravel content varies from 5-20%, the diameter of the gravel is about 1-10cm, and a small amount is greater than 10cm. The overall weathering of the gravel is strong. Below the land surface is mainly broken stone mixed with silty clay, and locally can be defined as gravel soil. Broken stone parent rock is mainly gray-dark gray marl, followed by gray-gray white sandstone, occasionally purple mudstone, the content of the breakstone is about 40-70%, and the local content can reach 80-90%.

Fig. 4. Silty clay with gravel

3.2. Slip zone characteristics

At present, Liujiabao landslide is in the weak deformation stage as a whole, but no obvious deformation intensification has been observed in recent years and there is no obvious through crack on the side boundary of landslide. According to the exploration, drilling ZK03 revealed slight scratches and mirror signs, drilling ZK01, ZK02, ZK04 only revealed the soft layer of gravel soil with high clay content, the gravel grinding has roundness, and no obvious signs were revealed (see Figure 5). The spatial distribution pattern of the slip zone varies greatly depending on the location. The potential slip zone revealed is yellow-brown gravel soil with loose or slightly dense structure, gravel content of about 10-20%, particle size of 1-5cm, as subangular shape, gray-black marl of the parent rock, strong weathering degree of the gravel block and easy to be dispersed by hand. At the same time, the mirror and scratch extrusion deformation signs are seen, the mirror is smooth, there is a certain reflection, and the inclination is close to the level.

There is a large amount of groundwater in the slip zone, and the rock mass in the slip zone will be affected by strong weathering after being eroded by groundwater, etc. There is a large amount of gravel in the slip zone soil, which also leads to the existence of a large number of clay particles in the slip zone soil, resulting in decline in its shear strength, which in a sense reflects the sliding state of the slip zone soil and the cause of the slip zone soil.

Fig. 5. Mirror and scratch characteristics of ZK03

3.3. Landslide bed characteristics

The landslide bed lithology is mainly composed of moderately weathered marl, the surface rock is mostly strongly weathered, the rock mass is fractured and fissure developed, the lower part is generally moderately weathered, and the rock mass is relatively intact.

4. Research methods and test samples

In this study, two rock samples, ZK02 and ZK04, were selected (see Figure 6 and Figure 7), and the Sampling of Liujiabao landslide samples is shown in Table 1. The collected slip zone soil mainly consisted of gravel clay with a yellowish-brown color, whose mother rock was mainly marl with a particle size of 10 to 45 mm, accounting for about 40% to 50%. Due to the inhomogeneity of gravel composition and particle morphology in the slip zone soil, its influence on the characteristics of the slip zone soil is very complicated. After on-site exploration, combined with drilling data and lithology in the interior of the landslide area, the geological section is drawn, and the sample collection site and photos are marked in the diagram. In the design of this test, the influence of gravel on the test results is not considered temporarily.

The core of the study is the slip zone soil and its surrounding rock and soil mass. The mineral composition, principal quantitative element composition and trace element composition as well as the chemical composition of groundwater in the landslide area are investigated by X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF) and conventional chemical analysis.

Table 1. Sampling table of Liujiabao landslide samples

Sample number	Relative position/m	Lithology description	Colour	Remark
2-1	46.6-48.1	Gravelly soil	Ash black	Sliding mass
2-2	48.1-51.3	Silty clay	Tawny	Slip zone
2-3	51.3-51.5	Marl	Ash black	Landslide bed
4-1	49.0-49.6	Marl	Ash black	Sliding mass
4-2	50.8-58.3	Silty clay	Tawny	Slip zone
4-3	42.2-42.4	Marl	Ash black	Landslide bed

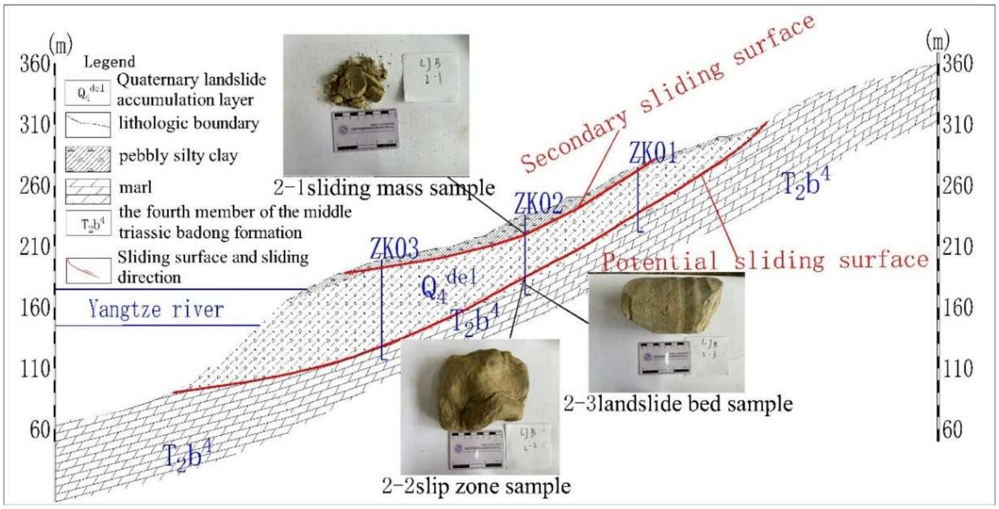


Fig. 6. Landslide geological section 1-1, sample collection site and its photos

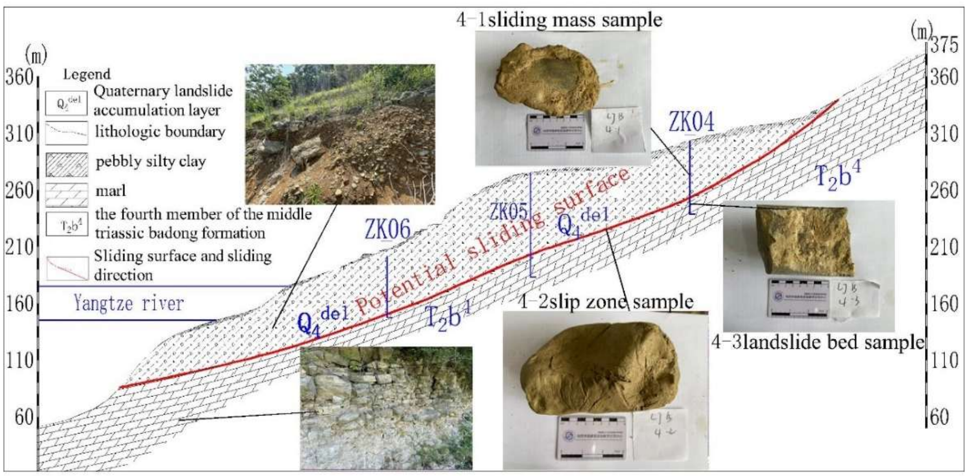


Fig. 7. Landslide geological section 2-2, sample collection site and its photos

5. Mineral Composition and Principal Quantitative Element Distribution Characteristics of Sliding Zone and Surrounding Rock and Soil

Generally speaking, there are two main causes of slip zone soil. One is that when the sliding mass slides, due to its own friction rupture, fine powdery particles are formed on the sliding surface. Second, in the relatively stable stage of the slope, water flows in the fine cracks of the rock mass due to the strong chemical weathering inside the landslide. In the long-term process of water-rock reaction, accompanied with the formation of a large number of secondary clay minerals, the whole rock takes place in argillation and eventually forms weak interlayers. In order to explore the genesis and mechanical property changes of slip zone soil, this paper is based on in-depth comparative analysis of mineral composition and conventional geochemical elements as well as water-rock interaction mechanism.

5.1. Mineral composition of slip zone soil and surrounding rock and soil mass

The core of the study of slip zone soil is its clay mineral composition, especially montmorillonite, which is a well-known expansive material because of its significant influence on the strength and formation process of slip zone soil. Expansive minerals like montmorillonite expand when wet. Previous studies on the role of expansive clay minerals in landslide occurrence show that even a small amount of expansive clay minerals in soil will have a great effect on its strength behavior. The results show that the soil in section 1, slip zone soil mainly contains quartz, dolomite, illite, smillonite, kaolinite, and calcite. Section 2 does not contain dolomite, other minerals are of the same type, and the sliding mass minerals are similar to the landslide bed minerals. The proportion of clay minerals of different types and their combination forms are different, which is because the sedimentary environment and weathering of the mother rock in the process of soil formation in each region are different, the details are shown in Figure 8 and Figure 9.

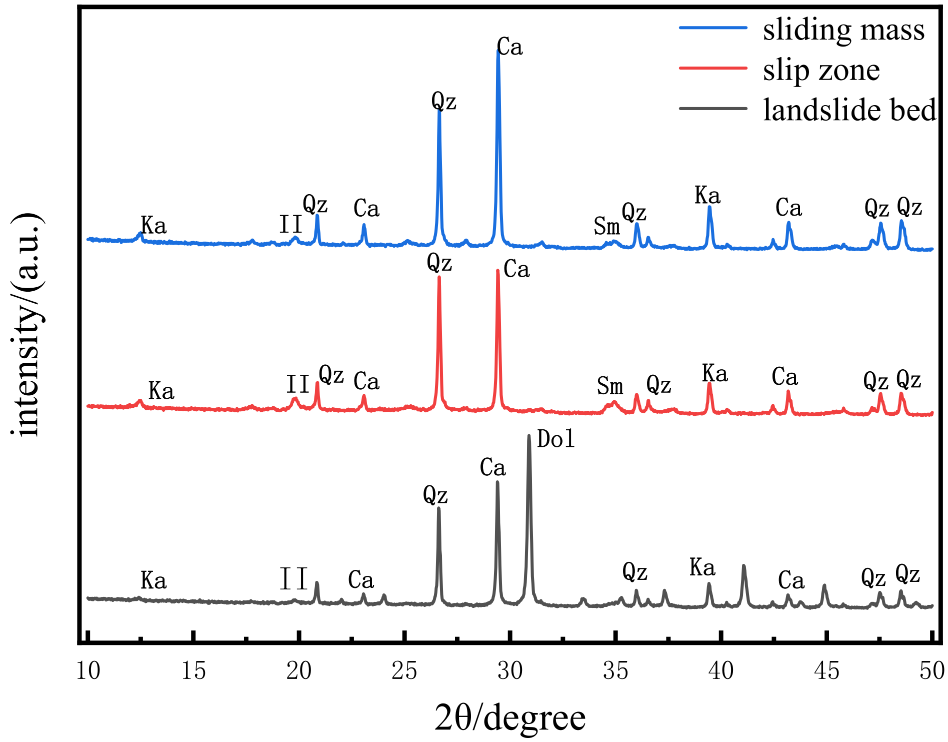


Fig. 8. Diffraction pattern of ZK02 sample from Liujiabao landslide

P.S. Qz: quartz; Ca: calcite; Dol: dolomite; II: illite; Sm: montmorillonite; Ka: kaolinite

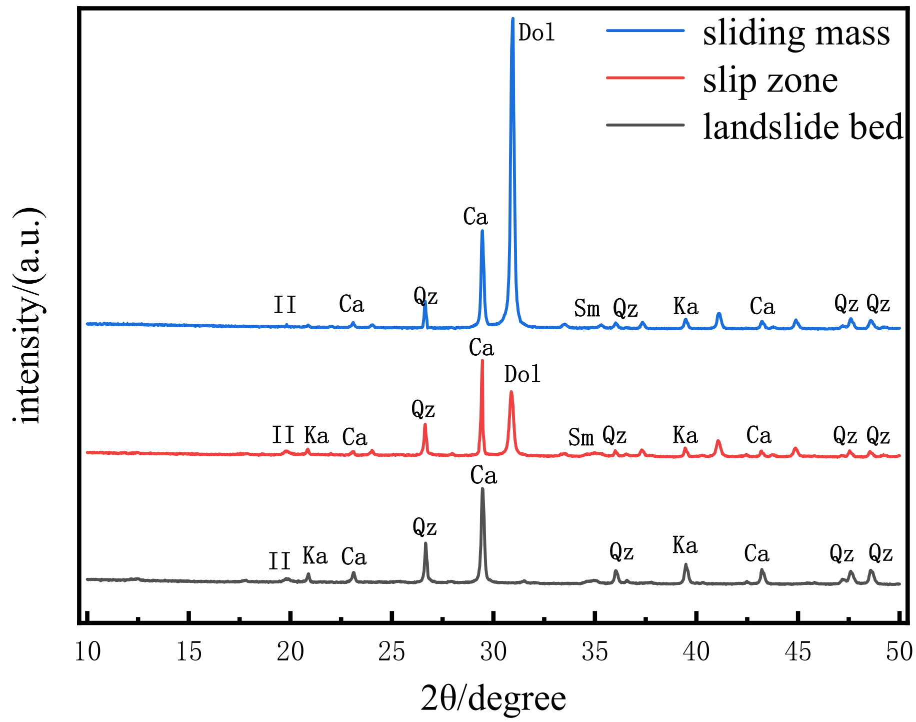


Fig. 9. Diffraction pattern of ZK04 sample from Liujiabao landslide

P.S. Qz: quartz; Ca: calcite; Dol: dolomite; II: illite; Sm: montmorillonite; Ka: kaolinite

By comparing the mineral composition of the two groups of slip zone soil, sliding mass and bedrock below the slip zone, it is found that slip zone soil is mainly composed of quartz and calcite, accompanied by dolomite, and secondary clay minerals include illite, kaolinite and montmorillonite, while no primary orthoclase minerals have been detected. In contrast, the bedrock minerals at the bottom of the landslide bed are dominated by quartz, calcite and dolomite, while the secondary clay minerals are kaolinite, illite and montmorillonite. The accumulation body above the slip zone is mainly composed of cultivated soil and contains only quartz, calcite, illite and kaolinite, but lacks montmorillonite. In all samples, illite, as a key clay mineral, is a relatively stable mineral that is transformed from potassium feldspar through strong physical weathering and erosion under weakly alkaline and arid climate conditions, showing a low degree of weathering. The reaction formula is as follows:

$$3K\left[AlSi_3O_8\right]+2H^+ +12H_2O=6H_4SiO_4+KAl_3Si_3O_{10}\left(OH\right)_2\left(illite\right)+2K^+ \quad (1)$$

5.2. *Composition characteristics of main and trace chemical elements of slip zone soil and surrounding rock and soil bodies*

When the main element oxide content is used to measure the element abundance, it is observed that the element distribution inside the landslide has the following characteristics. As shown in Figure 10, compared with the sliding mass and the landslide bed, the content of Na^+ and K^+ in the slip zone is significantly lower, while the content of Al^+ is slightly increased. The main components of the sliding zone soil of Liujiabao landslide are SiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O, Na_2O, MgO, and a small amount of P_2O_5 and TiO_2. Compared with the sliding mass and the landslide bed, the content of Na^+ and K^+ in the slip zone is the lowest, and the content of Al^{3+} is slightly higher. From the direction of sliding mass, slip zone and landslide bed, the content of element Ca^{2+} showed a gradually decreasing trend, the content of Si^{4+} increased slightly in the slip zone, and the content of Fe^{3+} showed an increasing trend, and the relative content of these elements was basically the same in the slip zone, sliding mass and landslide bed. The content of other elements had no obvious change characteristics.

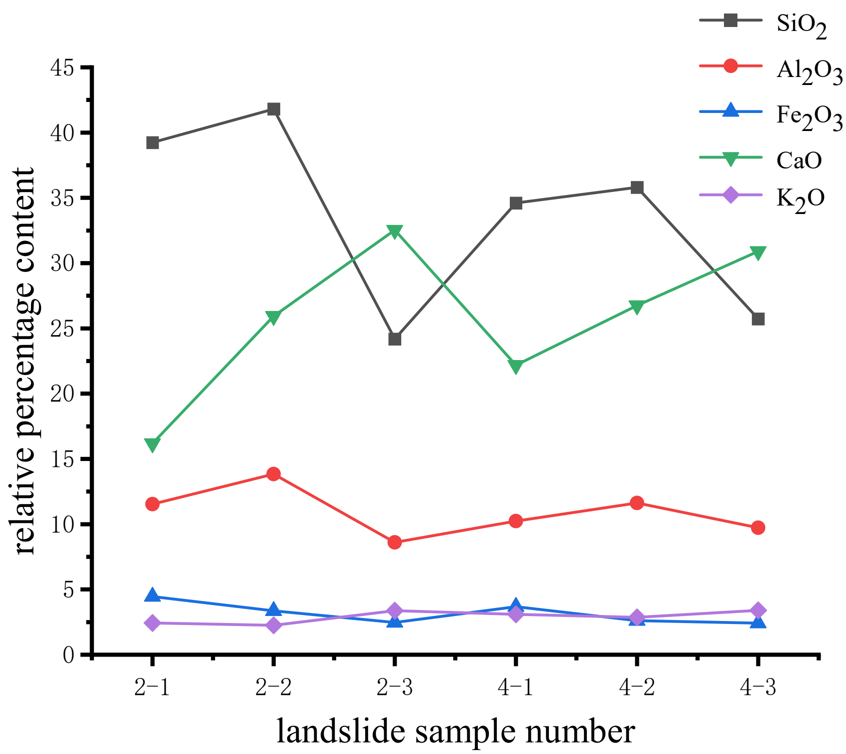


Fig. 10. Relative percentage content of chemical composition of Liujiabao landslide

According to the results of previous studies, the ratio of silica-aluminum elements in the pure known typical clay minerals is certain, kaolinite is 2, illite is 3, montmorillonite is greater than 4, and the molecular ratio of silica-aluminum in the calculated sample is greater than 3 and less than 4, indicating that the mineral composition is dominated by illite. The change trend of Al_2O_3/K_2O can reflect the change trend of illite content. From landslide bed to slip zone, if the ratio increases, the illite content may increase. And from slip zone to sliding mass, if the ratio decreases, the illite may transform into illite and montmorillonite mixed layer. From the sliding mass to the slip zone and then to the landslide bed, the content of Ca^{2+} decreased gradually. The content of Si^{4+} in the slip zone was slightly increased. The content of Fe^{3+} showed an increasing trend, and the relative content of these elements remained roughly the same in the slip zone, sliding mass and landslide bed. There was no significant change in the content of the remaining elements.

From the sliding mass to the underlying bedrock layer, the content of SiO_2 increases significantly in the region of slip belt, indicating that there may be more soluble salts. When the chemical composition of the slip zone is analyzed, the continuous flow of groundwater must cause the migration and deposition of easily soluble and highly active elements in the rock and soil.

At this stage, the slip zone of Liujiabao landslide is in an oxidizing environment, because the ratio of trace elements in the slip zone soil is shown in Table 2, and the chemical element composition of slip zone soil and upper and lower rock and soil mass is shown in Table 3, in which U/Th ratio <0.75, V/Cr ratio <2, Ni/Co ratio <5, and Sr/Cu ratio range from 1 to 10, which proves that the environment in the slip zone at this time is an oxidizing and warm and humid environment. Th and U can better represent the redox conditions of the soil, Th is enriched on the surface, and Th generally does not migrate under oxidation conditions, and a small amount of Th will migrate through colloidal binding and biochemical action. U has a strong migration ability under oxidation conditions, so Th/U can well represent redox conditions. The higher the ratio, the stronger the oxidation and the stronger the migration ability of water. This is consistent with the characteristics of trace elements, indicating that the slip zone soil is in a warm and humid environment, which is very conducive to the formation of slip zone soil, but very unfavorable to the overall stability of landslide.

Table 2. Table of trace elements in slip zone soil

Sample number	X2-2	X4-2
U	3.65	3.17
Th	13.10	7.50
V	75.40	60.20
Cr	69.70	43.50
Ni	35.60	26.40
Co	10.90	9.27
Sr	156.00	192.00
Cu	67.90	19.20
U/Th	0.27	0.42
V/Cr	1.08	1.38
Ni/Co	3.27	2.85
Sr/Cu	2.24	9.53

P.S. The unit of trace element is μg/g, and the test instrument is PlasmaQuant-MS Elite

Data source: Institute of Geochemistry, Chinese Academy of Sciences.

Table 3. Chemical element composition of slip zone soil and upper and lower rock and soil mass

No.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	LOI	SUM
	%	%	%	%	%	%	%	%	%	%	%	%
2-1 Sliding mass	39.24	11.54	4.46	1.98	16.18	0.30	2.43	0.063	0.082	0.276	23.12	99.67
2-2 Slip zone	41.80	13.84	3.36	1.58	25.94	0.20	2.26	0.171	0.944	2.327	7.07	99.49
2-3 Landslide bed	24.19	8.61	2.47	3.51	32.53	0.31	3.37	0.024	0.096	0.524	23.94	99.57
4-1 Sliding mass	34.61	10.24	3.68	2.01	22.18	0.11	3.10	0.042	0.086	0.375	23.49	99.93
4-2Slip zone	35.81	11.63	2.61	1.52	26.75	0.10	2.87	0.029	0.046	0.272	17.91	99.55
4-3 Landslide bed	25.74	9.73	2.42	2.68	30.91	0.32	3.40	0.029	0.093	0.443	23.93	99.70

6. The influence of groundwater on the formation of slip zone

6.1. Corrosion evaluation of groundwater

It is estimated that the shear outlet elevation of the front of the Liujiabao landslide is about 90m, which is lower than the lowest water level of the Yangtze River. The change of reservoir water level can cause significant changes in the groundwater level in the landslide body. The role of groundwater should not be ignored, which acts as a lubricant and softener, causing the contact zone to soften and mud, thus forming a potential slip zone and reducing its internal friction angle and shear strength, then reducing the sliding resistance. In addition, this situation will also lead to the increase of hydraulic gradient of groundwater inside the landslide, which will further increase the pressure of pore water and enhance the sliding driving force of landslide. These combined effects can cause the slope to deform and eventually lead to landslides. The stability of the whole landslide has an important relationship with the impoundment of the Three Gorges Reservoir.

Two groups of groundwater samples were taken for water quality analysis, and the water intake points were SW07 and SW08. Analysis results of hydrographic point water sample SW07 and SW08 (Table 4).

Table 4. Simplified analysis table of water samples

Ca^{2+}	$Na^{++}K^{+}$	Mg^{2+}	$S04^{2-}$	HCO^{3-}	Cl^{-}	Free CO_2	PH
88.28	45.33	15.87	27.83	337.09	12.02	5.19	7.49
91.90	40.00	15.77	157.55	247.04	10.46	4.32	7.18

Based on the analysis of the ionic chemical composition of the groundwater taken from the slip zone, according to the analysis of water chemical properties, the cations in the groundwater in this area are mainly composed of Ca^{2+}, K^{+}, Na^{+} and Mg^{2+}, while the anions are mainly HCO^{3-}, SO42- and Cl^{-}. The main hydrochemical type of the groundwater is HCo_3-Ca type. The chemical composition of groundwater is mainly original from the weathering dissolution of carbonate and silicate minerals, followed by the weathering dissolution of rocks. In clays with higher calcium carbonate content, the pH value is determined by the hydrolysis of calcium carbonate.

$$CaCO_3 + H_2O \leftrightarrow Ca^{2+} + HCO_3^- + OH^- \quad (2)$$

The chemical action of groundwater, cation alternating adsorption and human production and life jointly affect the chemical characteristics of groundwater. The groundwater quality in the slip zone is alkaline, and the rainwater is weakly acidic.

6.2. Chemical characteristics of groundwater

Clay minerals and calcite in the landslide have a significant impact on water, and the change of their content is particularly noteworthy, which can well indicate the development of the slip zone and the activity of groundwater. The slip zone has a higher clay content, and the permeability is less than that of the upper and lower soil layers, which is equivalent to the waterproof layer. When rainwater penetrates into the sliding surface through the upper soil layer, it accumulates, forming water-rock interaction at the slip zone. It results in significant changes in the composition of groundwater and rainwater.

This region has abundant precipitation, changeable topography, and relatively short groundwater flow and discharge path. In this environment, feldspar in landslide rocks will be directly converted into clay minerals after chemical weathering, such as the process of feldspar to kaolinite. Therefore, compared with the material of sliding mass and landslide bed, the increase and decrease of feldspar and clay minerals in the slip zone may reveal the result of the chemical weathering of marl under the action of groundwater for a long time.

$$2KAlSi_3O_8\left(\text{potash feldspar}\right) + 2H^+ + H_2O \rightarrow Al_2Si_2O_5\left(OH\right)_4\left(kaolinite\right) + 2K^+ + 4SiO_2 \quad (3)$$

The groundwater activity in the landslide slip zone is frequent, and the process of feldspar hydrolysis and argillation is particularly active here. The results of water samples showed that the groundwater did not contain corrosive CO_2. The presence of swelling minerals in the study area will greatly support the occurrence of landslide. As analyzed above, there is no primary clay mineral in the slip zone, and the groundwater is weakly alkaline, indicating that the conversion of feldspar to illite may occur in the slip zone. Under the interaction between water and rock, the transformation of primary minerals generates a series of clay minerals, and some soluble ions will be released during this process. These ions are integrated into groundwater, where the cation is mainly manifested as Ca^{2+}, suggesting that anorthite is the main feldspar species. According to the X-ray diffraction analysis and comparison between the slip zone soil and the sliding bed bedrock, in the slightly alkaline underground environment, the phenomenon of the gradual transformation of antrite into illite is observed in the slip zone area, accompanied by the transformation of montmorillite into illite:

$$Ca\left[Al_2Si_2O_8\right]+H_2CO_3+K^+\rightarrow KAl_3SiO_{10}(OH)_2+Ca^{2+}+HCO_3^- \tag{4}$$

$$montmorillonite+Al^{3+}+K^+\rightarrow illite+Ca^{2+}+HCO_3^-+Na^++Fe^{2+}+Mg^{2+}+Si^{4+} \tag{5}$$

The conversion of montmorillonite to illite in the slip zone resulted in a slightly alkaline fluid environment, which promoted the weathering of minerals such as feldspar and quartz, and gradually transformed montmorillonite into illite, thus promoting the key transformation of feldspar bedrock at the bottom of the slip zone into slip zone soil. The change of K^+ content in the slip zone is due to the presence of illite crystal structure in the slip zone soil. When the original mineral undergoes illillization, K^+ in its structure participates in cation exchange, and a large amount of K^+ is sucked into illite. Therefore, the change of K^+ content reveals the role of mineral illillization in the formation of slip zone soil. The increase of the non-mobile elements Si^{4+} and Al^{3+} in the slip zone region indicates the accumulation of clay minerals here, which may be related to the weathering of K^+ and Na^+ feldspar and the increase of secondary clay minerals. At the same time, this change suggests that there is an obvious lateral flow of groundwater inside the slip zone, carrying K^+ and Na^+ element losses. In the slip zone, calcite reacts chemically with carbon dioxide (CO_2) in the water, causing calcite to dissolve and its content to decrease. In addition, the dissolution of calcite requires slow groundwater flow to ensure that $CaCO_3$ can fully react with CO_2 in the water, which also reflects the change of Ca^{2+} characteristics during the clayification of skeleton minerals, and is directly related to the change of calcite content.

$$CaCO_3+CO_2+H_2O\rightarrow Ca^{2+}+2HCO_3^- \tag{6}$$

The chemical reaction between water and the soft interlayer, especially the dissolution of calcite and the loss of calcium ions, may weaken the binding force between soil particles and further reduce the shear strength of the zone of weakness. After the formation of the zone of weakness, the long-term accumulation of groundwater makes this area continuously subjected to chemical and physical effects, such as the increase of clay content due to hydrolysis. And then gradually reduce its shear strength. As rainfall permeates, pore water pressure increases, causing the soil to soften. Once the shear strength is unable to withstand the shear stress applied to it, a slip zone can form, resulting in overall instability.

Both the activity of landslide and the effect of groundwater are closely related to the particle composition of soil in the slip zone, and the change of particle size will significantly affect the physical and mechanical properties of the slip zone soil. By observing the origin of slip zone soil, we find that it is mainly shaped by mechanical crushing caused by landslide movement and chemical weathering of rock and soil, which shapes the unique structure and physical and mechanical properties of slip zone soil. In other words, any change in the physical and mechanical properties of slip zone soil can reflect its formation process. The core concerns of the experiment include the natural water content, natural density, specific gravity, natural pore ratio and saturation of the slip zone soil.

Table 5. Summary of physical properties of samples ZK02

Sample number	Natural water content	Natural density	Saturation density	Dry density	Specific gravity	Natural void ratio	Saturation
	w0/%	ρ0(g/cm3)	ρ0(g/cm3)	g/cm3			

2-1	5.6	2.15	2.27	2.04	2.69	0.321	46.9
2-2	14.8	1.99	2.09	1.73	2.7	0.558	71.7
2-3	4.74	2.72	2.51	2.42	2.53	11.88	4.87

Table 6. Summary of mechanical properties of the slip zone soil

Sample number	Natural shear resistance		saturated shear resistance	
	cohesive strength/kPa	internal friction angle/°	cohesive strength/kPa	internal friction angle/°
2-2	23.1	17.5	15.5	10.8
4-2	26.2	18.6	19.3	11.6

Table 7. Summary of physical properties of samples ZK04

Sample number	Natural water content	Natural density	Saturation density	Dry density	Specific gravity	Natural void ratio	Saturation
	w0/%	ρ0(g/cm3)	ρ0(g/cm3)	g/cm3			
4-1	3.3	2.2	2.33	2.13	2.67	0.254	34.7
4-2	17.2	2.1	2.12	1.79	2.7	0.512	91
4-3	4.67	2.72	2.49	2.38	2.50	12.44	4.95

The data show that the physical properties of the slip zone soil are significantly different from the samples from other regions. By comparing Table 5 and Table 6, it can be seen that the natural water content of the slip zone soil exceeds the samples of the sliding mass and landslid bed, suggesting that the rock and mineral structure in the slip zone has intensified changes due to the action of groundwater over a long period of time, which may give rise to different types of clay minerals, thus reducing the mechanical strength of rock and soil and forming fragile interlayers, which is consistent with the previous analysis. The natural density, saturated density and dry density of slip zone soil are lower than that of sliding mass and landslid bed samples. The natural pore ratio and saturation are higher than that of the sliding mass, and the pore ratio is in the range of 0.5 to 0.9, indicating that the slip zone soil in this landslide area belongs to medium compressibility soil. If there is a large amount of rainfall in the rainy season, the saturation of the slip zone soil will increase, and then absorb more rain, increasing the weight of the landslide, which may lead to greater compression of the slip zone soil, and further affect the stability of the landslide. In addition, Table 7 shows the summary of physical properties of samples ZK04.

7. Landslide activity trend prediction

According to the previous landslide deformation detection results, the amount of landslide deformation is very small, but according to the analysis results, there are generally rich calcite and illite in the slip zone, which indicates that the lasting physical and chemical interaction between groundwater and the slip zone materials will continue to promote the accumulation of illite-montmorillonite layer minerals in the slip zone, and make more calcite dissolve. And landslide is also in an oxidizing environment, which leads to the migration of a large number of elements and a series of chemical reactions. On this basis, combined with field geological survey and laboratory test analysis, it is believed that clay minerals in the slip zone soil are one of the important reasons leading to the instability and failure of landslide. The front and boundary of Liujiabao landslide are affected by tectogenesis, and the cutting of topographic gullies and valleys strongly forms the air condition, which shows slope landform. Under the condition of rainfall, rainwater is easy to collect at the landslide front, and the fracture of landslide rock mass and the development of joint fissure provide a channel for water infiltration. Under the condition of reservoir water level fluctuation, landslide will be affected by dynamic water pressure, hydrostatic pressure and pore water pressure on the slope surface, which will reduce the stress state of landslide, resulting in a decrease in the mechanical strength of slip zone soil. In addition, the rural road built in the region traverses the middle of the slope area, and reclaim wasteland on the slope, destroying the original topography and vegetation. On the one hand, the geological ecology is out of balance, and on the other hand, the drainage conditions of surface water are destroyed. In addition, local residents build houses on the slope, rural roads and other engineering activities. These conditions are not conducive to the stability of landslide, so the shear strength of the slip zone soil continues to decline, which may lead to the intensification of landslide creep deformation.

8. Conclusion

The clay minerals contained in the slip zone soil show that in the whole region, the rock and soil bodies in the main slip zone often suffer shear failure during the landslide process, which causes the feldspar and other minerals that are easy to weather to be gradually decomposed under the weathering effect of groundwater, and then transformed into clay minerals. At the same time, the rock structure is changed, its mechanical properties are reduced, and a fragile interlayer is gradually formed into the slip zone soil. The mineral composition characteristics of slip zone soil reveal that the formation of slip zone soil, especially clay minerals, requires specific material conditions and dynamic environment.

Water sensitive minerals such as calcite, clay minerals and feldspar, as well as active ions such as K^+, Na^+ and Ca^{2+}, can be used as key minerals and chemical markers to identify the interaction between water and soil in the formation of slip zones. Water-rock interaction promotes the movement and accumulation of clay minerals in undesirable geological bodies, and its influence on landslide should not be underestimated.

The characteristics of trace elements contained in the slip zone soil of Liujiabao landslide are U/Th ratio of 0.27~0.42, V/Cr ratio of 1.08~1.48, Ni/Co ratio of 2.57~3.27, Sr/Cu ratio of 2.24~9.54, in which U/Th ratio <0.75, V/Cr ratio <2, Ni/Co<5. The Sr/Cu ratio is between 1 and 10, which reflects that there is an oxidizing and warm and humid environment in the slip zone of Liujiabao landslide, which will cause some clay minerals to accumulate and reduce the mechanical strength of the slip zone soil.

The chemical composition of slip soil zone is mainly SiO_2, Al_2O_3 and $CaCO_3$, indicating that quartz minerals are relatively enriched in coarse particles, while alumino-silicate clay minerals are relatively enriched in fine clay particles. In addition, the existence of active elements such as K, Na, Ca and Mg may promote the transformation of illite into hydrophilic clay minerals, such as vermiculite and montmorillonite. The hydrophilicity of the slip zone soil is enhanced, and the engineering properties of the landslide are further worsened.

Conflict of interest

There is no potential conflict of interest in our paper and all authors have seen the manuscript and approved to submit to your journal. We confirm that the content of the manuscript has not been published or submitted for publication elsewhere.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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