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Weathering Characteristics of Sloping Fields in the Three Gorges Reservoir Area, China*1

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ABSTRACT

For the purpose of understanding the weathering characteristics of surface layers in purple mudstone sloping fields of the Three Gorges Reservoir area of China, oxide content of major elements, composition of clay minerals, magnetic susceptibility, and difference in weathering characteristics of surface layers under different slope gradients were determined. The results showed that the oxide content of Si, Al, and Fe ranged from 60% to 75% and the weathering coefficient with depth showed no trend along the slope gradient. Also, for gentle (10° and 15°) and intermediate (25° and 40°) slopes the clay relative diffraction peak for kaolinite at the surface between 0–10 cm and 10–20 cm declined with an increase in slope gradient, while the relative diffraction peak for kaolinite in weathered layers on steep slopes (50° and 60°) disappeared altogether. Magnetic susceptibility decreased with increasing depth and, for a given depth layer, decreased with an increase in slope gradient. Analysis of the oxide content, weathering coefficients, clay minerals, and magnetic susceptibility showed that in the Three Gorges Reservoir area, the pedogenesis of the weathering layer in purple mudstone sloping fields was weak with weaker soil formation going from gentle slope to steep slope.

Key Words: purple mudstone, sloping field, Three Gorges, weathering

Weathering characteristics in sloping fields has been a subject of study for many researchers (Clark and Small, 1982; Yang and Lu, 1992; Easterbrook, 1993; Liang *et al.*, 1993; He and Tang, 1998; Liu *et al.*, 1996; Lu, 2000; Moreau and Petard, 2004; Rech *et al.*, 2001; Shi *et al.*, 1998, 2002; Yokota and Iwamatsu, 2002; Atkinson *et al.*, 2003; Zhang *et al.*, 2004; Allen, 2005; He *et al.*, 2005). Much work has also been done on the weathering characteristics in the sloping fields of the Three Gorges Reservoir area in China (Chong *et al.*, 2002; Cai *et al.*, 1996; Compiling Committee of Fengjie County in Sichuan Province, 1995; Liu *et al.*, 1991; Shi *et al.*, 1991; Zhang *et al.*, 2002). However, most of the research achievements have focused on the formation characteristics, nutrients, land erosion of purple mudstone slopes in the Three Gorges, while only a few studies have focused on its weathering degree and characteristics. Therefore, it is necessary to further research the weathering characteristics of purple mudstone in order to understand how sloping land develops.

This research studied the surface layers of different purple mudstone sloping fields in the Caotang River Basin in Fengjie County of the Three Gorges Reservoir area. The fieldwork and sampling analysis of oxide content of major elements, clay mineral composition, magnetic susceptibility, and differences in weathering characteristics of surface layers under different gradients were determined to provide a basis for characterizing geomorphology, potential resource use, and an evaluation of the overall engineering geological conditions.

MATERIALS AND METHODS

Site description

The Three Gorges Reservoir area studied herein covers Yichang City, Zigui, Xingshan, and Badong

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counties in Hubei Province, and Wushan Mountain, Wuxi, Fengjie, Yunyang, Wanzhou, Kaixian, Zhongxian, Fengdu, Shizhu, Fuling, Wuling, Changshou, Yubei, Banan counties, Chongqing Municipality and Jiangjin City, which altogether comprise 20 counties, cities and districts. The total area is 5.67×10^4 km^2, of which 600 km^2 land area is submerged by the reservoir.

The Caotang River, located in Fengjie County of Chongqing Municipality, is the main stream on the northern embankment of the Yangtze River, and it is under the jurisdiction of Baidi, Caotang, and Fenghe in Fengjie County. The river has two main tributaries, namely, the Fenghe River and the Shima River. The main tributary is about 33.3 km long with an average gradient of 0.665%; the river basin area is 394.8 km^2; the average flow is 7.51 m^3 s^{-1}; and the total yearly flow is 0.237 billion m^3. There are abundant water and rich river networks in this area, and the average river network density is 0.79 km^{-2}. In this area the strata are composed of sedimentary rock, mostly belonging to the Badong group of the Middle Triassic. The geomorphological type is low mountain river basin. The climate here is mid-subtropical humid monsoon with an average temperature of 15 °C and average rainfall of 1 200 mm. The river basin consists mostly of steep slopes and dry land, or bushy grass slopes. As a result the vegetation is severely damaged with large amounts of land and water lost through frequent mudflows on the slopes and in the gorges area that raise the riverbed every year (Zheng and Shen, 1998).

Sampling and sample analysis

For the purpose of this study conducted in the Caotang River Basin, the slope was divided into three classes according to different slope gradients and six slopes were selected, that is, gentle slopes (10° and 15° gradient), intermediate slopes (25° and 40°), and steep slopes (50° and 60°). A sampling cylinder with an inner diameter of 9.5 cm and height of 50 cm was used to bore vertically into the weathering layers to obtain cylindrical soil samples. The sampling interval for each boring was 6 cm in gentle slope areas, 4 cm in intermediate slope areas, and 3 cm in steep slope areas. From each boring seven samples were collected, plus six surface layer soil samples on the six slopes, or totally 48 samples.

After soil samples were air-dried, ground, and then pressed onto the glass slices, the oxide content of major elements of the samples was examined by a VF320 X-ray fluorescence spectrum machine, produced by Shimadzu Company in Japan. Air-dried samples were rubbed and were then put into 10 mL cylindrical plastic boxes for pressing and weighing. Then they were tested by a Bartington Magnetometer MS2 type magnetic machine, produced in Germany with a low working frequency of 0.4 kHz. For an X-ray diffractometry examination a D/max-RA X-ray machine produced by Shimadzu Company in Japan was used to test the mineral content in clay. The magnetic testing work was conducted in the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Other testing work was performed at the Modern Analysis Center of Nanjing University, China.

RESULTS

Chemical composition and weathering coefficient

The composition of weathering layers in the study area were mostly oxides of Si, Al, and Ca, which accounted for 60%–75% of the total, followed by Fe_2O_3, MgO, K_2O, and Na_2O (Table I). There were also many secondary sediments of $CaCO_3$ (almost 35%), usually found in the 25° intermediate slope. Additionally, with slope gradients of 10° and mostly in the bottom layer (depth > 30 cm), there were some $CaCO_3$ sediments with the seepage. In the weathering layer of this same gentle slope, with an increase in depth there were some slight differences in oxide content, however there was no obvious trend.

For a given slope gradient, with increasing depth the weathering coefficients of silicon-aluminum, aluminum-iron, and silicon-iron changed slightly with no obvious trend. However, with different slope gradients (Table I) differences in chemical element movement was noted: from gentle, intermediate, and steep slopes, the average coefficients for SiO_2/Al_2O_3 were 6.14, 6.04, and 6.39, respectively; for

Al_2O_3/Fe_2O_3 4.68, 5.18, and 5.05, correspondingly; for R_2O_3/SiO_2 0.19, 0.19, and 0.18, in that order; and for SiO_2/Fe_2O_3 28.99, 29.64, and 32.33, respectively.

TABLE I

Mean oxide contents of major elements and weathering coefficients in the weathering layer for different slope gradients

Slope gradient	Layer[a)]	Oxide							Weathering coefficient			
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SiO_2/Al_2O_3	Al_2O_3/Fe_2O_3	R_2O_3/SiO_2	SiO_2/Fe_2O_3
		%										
10°	I	36.73	13.21	4.92	17.12	1.48	1.63	0.02	6.12	4.84	0.19	29.69
	II	28.73	10.58	3.66	26.40	1.36	1.47	0.02	6.14	4.59	0.19	29.22
	III	33.94	12.17	4.37	20.77	1.36	1.64	0.02	6.13	4.57	0.19	28.01
	IV	31.12	11.61	3.78	24.28	1.60	1.60	0.03	6.08	4.69	0.19	28.57
15°	I	35.82	9.89	3.54	21.92	1.66	1.73	0.07	6.15	4.38	0.19	28.57
	II	39.05	10.81	3.69	19.22	1.82	1.92	0.07	6.15	4.78	0.20	29.12
	III	41.61	11.49	3.81	17.55	1.96	1.95	0.05	6.16	4.80	0.19	29.10
	IV	38.66	10.73	3.68	19.72	1.82	1.90	0.06	6.16	4.81	0.19	29.65
25°	I	20.40	6.78	1.68	35.17	1.00	1.19	0.02	5.46	4.29	0.20	38.91
	II	19.96	7.35	2.10	35.66	1.06	1.21	0.02	6.17	4.78	0.19	26.47
	III	22.03	7.74	2.12	34.10	1.12	1.32	0.02	6.42	7.11	0.19	27.87
40°	I	37.30	10.93	2.81	20.43	2.07	2.19	0.15	5.80	4.33	0.20	27.24
	II	50.74	13.98	5.11	10.13	2.33	3.00	0.25	6.14	4.45	0.20	27.94
	III	55.41	14.65	5.30	6.60	2.53	3.14	0.34	6.26	6.10	0.19	29.40
50°	I	24.80	9.79	2.18	26.50	4.87	1.96	0.02	6.34	5.24	0.18	33.26
	II	27.96	10.16	2.92	23.98	5.17	2.00	0.03	6.42	4.94	0.18	31.77
60°	I	40.45	10.54	3.28	19.48	2.20	2.08	0.18	6.38	4.76	0.18	30.45
	II	39.40	10.44	3.31	20.15	2.24	2.08	0.18	6.41	5.27	0.18	33.83

a) Depth of sampling layer: I is 0–10 cm, II is 10–20 cm, III is 20–30 cm, and IV is greater than 30 cm.

Clay minerals

Clay minerals in the weathering layer mostly consisted of mica, vermiculite-montmorillonite, and kaolinite. Besides clay minerals, there were also some quartz and calcite. The clay mineral content changed with depth and slope gradient as the relative height of the diffraction peak for the clay mineral indicated (Table II).

TABLE II

Heights of diffraction peaks for clay minerals in the weathering layers for different slope gradients and depths

Mineral type	Layer[a)]	Slope gradient					
		10°	15°	25°	40°	50°	60°
		cm					
Mica	Surface	2.6[b)]	2.3	2.0	1.2	1.1	1.0
	I	2.5	2.6	2.0	2.0	0.7	0.8
	II	3.4	3.2	2.1	1.0	–	–
	III	3.4	3.2	2.3	1.0	–	–
	IV	3.1	3.1	2.5	0.9	–	–
Vermiculite-montmorillonite	Surface	2.6	2.7	2.4	2.3	2.0	2.0
	I	2.9	2.8	2.6	2.5	1.5	1.4
	II	4.1	4.1	3.0	1.9	1.1	1.4
	III	4.0	4.2	2.7	1.9	1.0	1.3
Kaolinite	Surface	1.4	1.3	1.1	1.0	–	–
	I	1.3	1.2	1.1	0.7	–	–
	II	0.9	0.9	0.7	0.6	–	–

a) Depth of sampling layer: I is 0–10 cm, II is 10–20 cm, III is 20–30 cm, and IV is greater than 30 cm;
b) The numbers in the table are average values.

Within the same gradient but at different depths, the diffraction peak heights of the clay mineral varied. For mica and vermiculite-montmorillonite, in the gentle slope area (10° and 15°) the heights of the diffraction peaks generally increased with an increase of depth to 30 cm; in the intermediate slope area (25° and 40°) they had no evident trend; and in the steep slope area (50° and 60°) they decreased with an increase of depth to 10 cm and 30 cm, respectively. However with kaolinite, except in steeper slope areas where there was no diffraction peak, the height of the diffraction peak decreased with an increase of the depth.

Looking at the diffraction peak height of clay minerals in the weathering layer for different gradient classes (gentle, intermediate, and steep) with an increase of gradient class, it has been noticed that the average diffraction peak heights of clay minerals always decreased.

Magnetic susceptibility

Table III presents the magnetic test results of the soil samples at different depths for different slope gradients. The results showed that with an increase in depth, the magnetic susceptibility of the 25°, 40°, and 60° gradients changed slightly (0.06–0.84 10^{-8} m^3 kg^{-1}), whereas in the 10°, 15°, and 50° gradients the changes were more substantial (up to 1.5–3.0 10^{-8} m^3 kg^{-1}) with no obvious changing rule. However at a particular depth with an increase of slope gradient, the magnetic susceptibility mostly decreased. Thus, except in Layer II at 15° and 60° slope gradients, there was an obvious decreasing trend with an increase in slope gradient.

TABLE III

Average magnetic susceptibility in the weathering layer for different slope gradients and depths

Item	Layer[a)]	Slope gradient					
		10°	15°	25°	40°	50°	60°
		10^{-8} m^3 kg^{-1}					
Magnetic susceptibility	I	27.15	18.25	15.75	12.43	9.48	7.45
	II	18.60	19.19	15.02	12.36	6.82	7.39
	III	28.64	19.73	15.86	12.81	–	–
	IV	28.07	20.76	–	–	–	–

[a)]Depth of sampling layer: I is 0–10 cm, II is 10–20 cm, III is 20–30 cm, and IV is greater than 30 cm.

DISCUSSION

The results of the weathering layers of purple mudstone in the Three Gorges Reservoir area showed that the major chemical composition of purple mudstone in Three Gorges Reservoir area consisted of Si, Al, and Ca oxides (Table I), which accounted for 60–75% of the total. Besides three types of oxides mentioned earlier, it was also observed that CaO content was relatively high in the study area, which was due to the following two aspects: on the one hand, the strata of the Badong group of the Middle Triassic were mostly formed in a shallow sea environment with the clay itself having a high content of Ca and on the other, the surface biochemistry process was very complicated with dissolved Ca^{2+} being redeposited.

As for the weathering crust with the same parent rock material, the magnetic susceptibility reflected the pedogenesis extent. Generally, the magnetic susceptibility value increased with an increase of pedogenesis. So, in the study area, the sequence of the pedogenesis was, gentle slope > intermediate slope > steep slope. For the same slope gradient, with an increase in depth, clay mineral content and magnetic susceptibility changed very slightly, and there were no obvious trends (Tables II and III). This meant that the age of the weathering layer in the study area was very young and pedogenesis was weak.

Clay mineral composition testing showed that the mica and vermiculite-montmorillonite contents were not as well defined as kaolinite (Table II). Hence, the kaolinite peak height was used as a better indicator of soil pedogenesis in the weathering layer. The higher the peak height was, the more was the kaolinite content, and the stronger the pedogenesis the weaker the surface erosion. Based on these changing characteristics of clay minerals in the weathering layer, it could be stated that with an increase in slope gradient class, the pedogenesis in the weathering layer decreased. This meant that in the gentle slope area the pedogenesis was the strongest among the three followed by the intermediate slope area and finally the steep slope area.

At the same time, with an increasing slope gradient, the diffraction peak height (Table II) and magnetic susceptibility (Table III) of kaolinite decreased. This indicated that from a gentle to an intermediate and then to a steep slope, the pedogenesis of weathering layer was becoming weaker and weaker, while surface erosion was becoming stronger and stronger. This was mainly because gentle slopes were less vulnerable to erosion, and hence deposits were easily kept in the weathering layer, making pedogenesis relatively strong. However, on steep slopes, the strata were more vulnerable to mechanical erosion such as weight. Thus, fresh strata were often seen and the pedogenesis in the weathering layer was relatively weak.

To some extent, the weathering coefficient (Table I) could reflect the weathering degree from surface to lower depths. Nevertheless in the study area, the depth of the section was limited, and it was not very accurate to use this as a judgment standard. The testing results from this study should just be used as a reference.

Finally, in order to improve the analysis accuracy for the degree of weathering, some of the advanced methods such as isotope method of $^{90}S_r$ and ^{137}Cs should be employed to determine the weathering speed and other factors.

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