Study on the Water-Rock Interaction Behavior of Xigeda Strata in Lamaxi Gully, Sichuan Province, China

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Abstract

Based on the test data of mineral, chemical and physical characteristics of Xigeda rocks in Lamaxi Gully, the rocks engineering properties are discussed. Combing with the immersion test, the water-rock interactions between the Xigeda rock specimens and deionized water are studied to provide more insight into the cause of the poor engineering properties of Xigeda rocks and the influence on the hydraulic erosion.

Keywords

Xigeda strata • Water-rock interaction • Headward erosion

377.1 Introduction

The Lamaxi Gully, which is distributed the Xigeda strata with poor engineering properties, is located in a section of the expressway from Ya'an to Lugu. The Xigeda strata are semi-diagenetic soft rocks and distributed in southwest China. The water-rock interactions between Xigeda rocks and fluid water take significant changes in chemical and physical properties of rocks, such as elemental migration, mineral transformation, structure failure and permeability change (Bucher et al. 2009; Göb et al. 2013; Gao et al. 2009; Huang et al. 2010; Newman and Mitra 1993; Zulauf et al. 1999). In a generalized way, water-rock interaction process can be described as a reaction between an aqueous fluid and a rock in its broadest sense (Corteel et al. 2005).

This study analyzed the mineralogical and chemical characteristics of Xigeda rocks. An immersion test was performed to examine the water-rock interactions. Furthermore, the hydraulic erosion mechanism in Lamaxi Gully was discussed based on the comprehensive experimental results. It is expected to provide some instructive significance for geological hazard treatments in Xigeda strata area.

377.2 Geological Setting

The Lamaxi Gully is located in Hanyuan County, Sichuan province, where belong to the transition zone between Western Sichuan Plateau and Sichuan Basin. The study area is in a subtropical and temperate mountain climate and a mean annual temperature of 17.8 °C. The mean annual rainfall is about 750 mm, while that in rainy season (from July to September) can reach 70–80 % of total rainfall in a year. Slope angles of the Lamxi Gully slopes on both sides are about 10°–30°, and the longitudinal slope of the gully is about 8–15° (Fig. 377.1). The Gully covering the Xigeda formation, Neogene System, which is belong to the semi-diagenetic soft rock. The Xigeda strata mainly consisted of gravel, sand and clay layer. From the field investigation, three typical samples were taken at depth of ~2.0 m in study area, using the grooving method with a cubic

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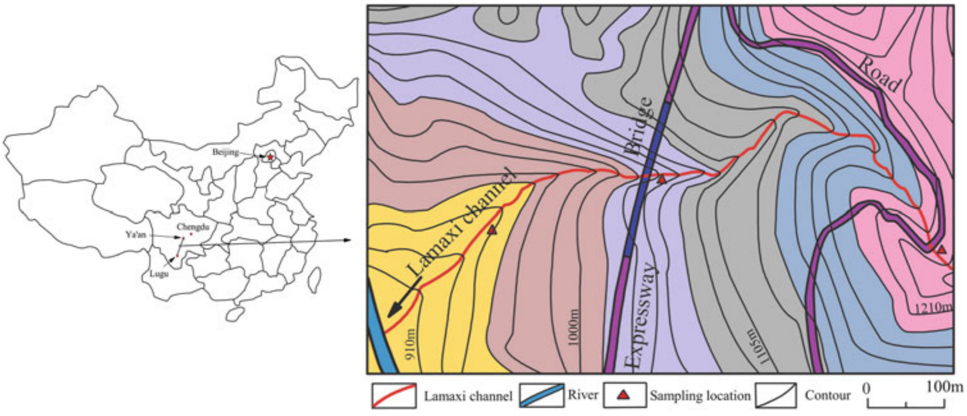

Fig. 377.1 Topographic map of Lamaxi Gully in Sichuan Province, Southwest China

Table 377.1 Concentrations of major elements of Xigeda rocks in Lamaxi Gully unit: %

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	CIA[a]
1	52.94	13.64	5.98	6.91	2.87	2.58	1.33	0.12	66
2	59.38	12.16	4.78	6.70	2.20	2.26	1.51	0.09	64
3	62.98	15.22	6.24	5.68	1.46	2.57	1.40	0.11	68

[a] CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, the oxides are given in molar ratio and CaO* represents its content in silicate, excluding CaO in carbonate and phosphate. When the CaO content is higher than that of Na_2O, the CaO* is equal with Na_2O, otherwise, $m_{CaO^*} = m_{CaO}$ by McLennan (1993)

dimension. The samples belong to the weak to middle weathering degree from the chemical index of alteration (CIA) in Table 377.1.

377.3 Methods

377.3.1 Chemical and Physical Analysis

The samples taken in study area were placed in paper bowel and dried on ventilated place. The dried samples were grinded into powder by pollution-free grinder and passed through a 100-mesh sieve. Major mineral constituents of the samples were determined by the X-ray diffraction (XRD) with a randomly oriented powder mount. The mounts are typically X-rayed between the angles of 5° and 60° using Cu-Kα radiation at a scanning rate of 2° per minute.

Eight major oxides (Ca, Mg, Fe, Mn, K, Na, Al and Si) were quantitatively analyzed. The contents of Ca, Mg, Fe, and Mn oxides were measured using the Hitachi Z-5000 atomic absorption spectrometry; that of K and Na oxides were measured using Hitachi 180-80 flame emission spectrometry. The contents of Al and Si oxides were measured by chemical titration and gravimetric method, respectively.

The particle size was determined using the hydrometer method and diffusion method. The particle settling velocity was calculated by Stokes formula.

377.3.2 Immersion Test

The samples were grinded into powder and passed through a 50-mesh sieve. The powders and deionized water at the ratio of 1:20 were mixed in a glass container. The container was sealed after most of the powders dissolved. 10–25 mL solution samples were collected using a pipette at the intervals 1–2 day to measure their concentrations. In order to keep the water and powder ratio at the constant, the immersion solution was mixed sufficiently before sampling. The sampling solutions were measured after filtration and impurity removing. The Ca^{2+}, Mg^{2+} and HCO_3^- were measured by the chemical titration method, and the SO_4^{2-} was measured by the turbidimetric method.

377.4 Results

377.4.1 Mineralogy

Minerals identified are illustrated schematically in Fig. 377.2. The primary minerals consist of quartz, albite, K-feldspar, calcite, dolomite, and secondary minerals including smectite, illite, kaolinite and some magnesium iron oxides. In the rock weathering process, K-feldspar, albite, calcite and dolomite are generally depleted and some clay minerals are formed. Kaolinite was the major clay mineral in the rock samples.

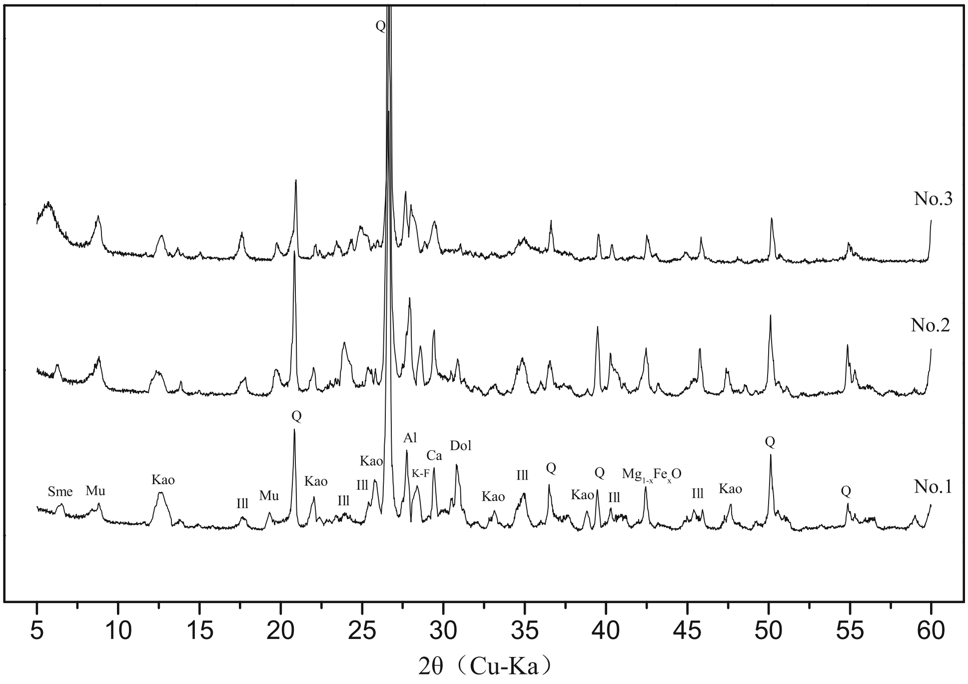

Fig. 377.2 Characteristic of X-ray diffraction pattern for samples in Xigeda strata, Lamxi Gully. *Q* quartz, *Al* albite, *K-F* K-feldspar, *Mu* muscovite, *Ca* calcite, *Dol* dolomite, *Sm* smectite, *Ill* illite, *Kao* kaolinite, $Mg_{1-x}Fe_xO$ magnesium iron oxide

377.4.2 Chemical Constituent

The chemical contents of eight major oxides are shown in Table 377.1. The alkali element (Na_2O and K_2O) content ranges from 1.40 to 2.58 %. The alkali earth element (MgO) content ranges from 1.46 to 2.87 %. CaO content ranges from 5.17 to 6.91 %. It indicates the Na, K and Mg have depleted in the long geological time. The relative higher Ca element is probable related to the existence of carbonate minerals. FeO content ranges from 3.74 to 6.24 % and Al_2O_3 content ranges from 12.16 to 15.22 %. Al and Fe elements aren't mobile so they might be the residual elements.

377.4.3 Particle Size Analysis

The particle size of Xigeda rock samples are listed in Table 377.2. The particle size ranging from 0.075 –0.005 mm takes the highest proportion, that ranging from 2 to 0.075 is relative less. The result indicates Xigeda rocks are mainly composed of sand and silt. The average proportions of sand, silt and clay particle are 14.1, 78.3 and 7.6 %, respectively. The Xigeda strata are sensitive to water from previous researchers (Gao et al. 2009; Hao and Wang 2010). What's more, because silt is relatively uniform and sensitive to water, the Xigeda strata are easy to erosion and disintegration. Consequently, the ability of Xigeda rocks and soils to resist erosion of rainfall is weak as accompany with hydration, swelling and dispersion.

Table 377.2 Analysis of particle size unit: %

Sample No.	2–0.075 (mm)	0.075–0.005 (mm)	<0.005 (mm)
1	19.6	66.3	14.1
2	10.7	84.1	5.2
3	12.1	84.5	3.4

377.4.4 Immersion Result

The Ca^{2+}, Mg^{2+}, HCO_3^- and SO_4^{2-} concentration and pH value are shown in Fig. 377.3. The pH value gradually increases from 7.1 to 8.2 through the whole immersion process (Fig. 377.3a), indicating the Xigeda rocks are alkaline. The concentration of Ca^{2+} exhibits terraced curve (Fig. 377.3b). The first step shows that Ca^{2+} increased rapidly in the first day and got equilibrium state at day 2–4. It is inferred that Ca^{2+} was dissolved and released into the solution at this stage. The second step shows Ca^{2+} increased sharply from 0.4 to 0.6 mmol/L from day 5 to day 7, and then reached a new equilibrium. The changes at the second stage are inferred to the ion exchange. The concentration of Mg^{2+} increased gradually and reached to 0.6 mmol/L in the first 7 days. After the concentration peak, Mg^{2+} began to decrease and got equilibrium with 0.34 mmol/L finally. The decrease in Mg^{2+} concentration is deduced that Mg^{2+} combined with OH^- to produce $Mg(OH)_2$ precipitate from the SEM-EDS observation. The HCO_3^- concentration curve is similar with that of Ca^{2+}, which could be divided to two steps (Fig. 377.3c). The first stage kept at a relative low lever, about 1.4 mmol/L. At the second stage, it's increased

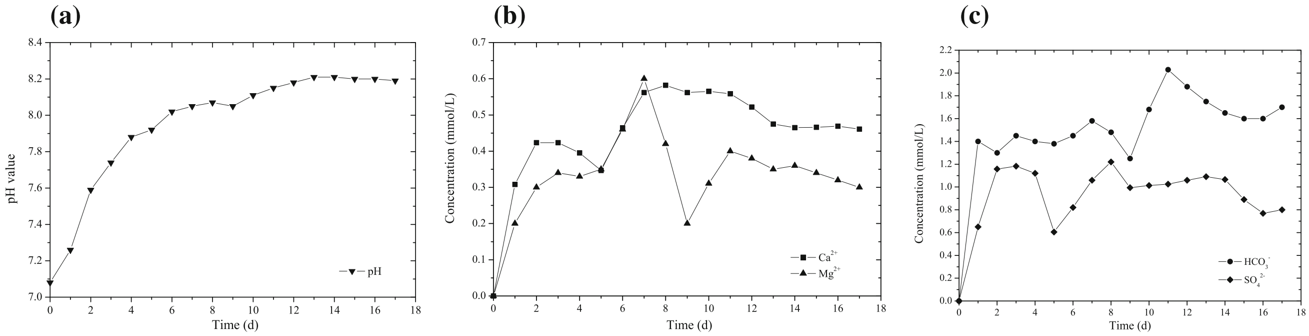

Fig. 377.3 The diagram of pH value, Ca^{2+}, Mg^{2+}, HCO_3^- and SO_4^{2-} concentration versus time

to a higher concentration and then kept stable. As the water-rock reaction is in a sealed environment, dissolved CO_2 in the solution should be less and limited. As a result, it indicates HCO_3^- comes from the minerals or reaction products, such as illite and kaolinite. The concentration of SO_4^{2-} fluctuates in some ranges (0.6–1.2 mmol/L). Based on the mineral analysis, it shows that the bearing-sulfur minerals are not detected in the rock samples. Therefore, it is inferred that the SO_4^{2-} comes from the rainfall.

377.5 Discussion

377.5.1 Water-Rock Interaction

The Xigeda strata are sediments in the interglacial period. The major mineral is silicate, which is prone to hydrolyze in the water-rock interactions. The important reactions are listed as following:

$$\underset{\text{K-feldspar}}{K(AlSi_3O_8)} + 4.5H_2O + H^+ \rightarrow 0.5\underset{\text{Kaolinite}}{[Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O]} + K^+ + 2H_4SiO_4 \tag{377.1}$$

$$\underset{\text{Albite}}{Na(AlSi_3O_8)} + 4.5H_2O + H^+ \rightarrow 0.5\underset{\text{Kaolinite}}{[Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O]} + Na^+ + 2H_4SiO_4 \tag{377.2}$$

$$\underset{\text{Illite}}{K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2} + 3.15H_2O + 1.1H^+ \rightarrow 0.6K^+ + 0.25Mg^{2+} + 1.15\ \underset{\text{Kaolinite}}{[Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O]} + 1.2H_4SiO_4 \tag{377.3}$$

$$\underset{\text{Muscovite}}{KAl_2(AlSi_3O_{10})(OH)_2} + 1.5H_2O \rightarrow 1.5\underset{\text{Kaolinite}}{[Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O]} + K^+ \tag{377.4}$$

From the reactions above, it is seen that the clay mineral kaolinite is produced from the water-rock interactions. These reactions could bring mineral transformation and engineering property changes. Nevertheless, the chemical reactions are ubiquitous in natural weathering process. From the angle of rock mechanics, the water-rock interaction can take considerable changes in mechanics parameters (e.g. internal friction angle, cohesion, shear strength).

Besides, the physical mechanic property of the rocks is associated with the chemical compositions as well. The cohesion of rock increases with the concentrations of Fe_2O_3, MgO, MnO and Na_2O increasing, while decrease with the concentrations of K_2O, CaO and SiO_2 increasing (Ye et al. 2006). Based on the chemical constituent results in Table 377.2, it indicates the sum of Fe_2O_3, MgO, MnO and Na_2O ranges from 8.21 to 10.30 %, and that of K_2O, CaO and SiO_2 ranges from 62.43 to 68.34 %. Thus, the cohesion of Xigeda rocks is inferred to be less in Lamaxi Gully. What's more, the alkali and alkali earth element are unstable elements. The sum of Na_2O, K_2O and CaO ranges from 9.65 to 10.82 %, indicating these elements can migrate by flow aqueous and make the rock pores, fractures and joints failure gradually.

377.5.2 The Influence on the Headward Erosion in Lamaxi Gully

In rainy season, rainfall flows into the Lamaxi Gully and reacts with the Xigeda rocks. Under the impact of water-rock interactions and flow transportation, the gully bed is eroded to become "V" shape and headward erosion. This phenomenon is called hydraulic headward erosion, which mainly refers to the down-cutting to the gully bed under the hydraulic pressure. The hydraulic erosion damages the stability of the gully slope on both sides through the geological disasters such as landslides, collapse and debris flow. The other erosion is

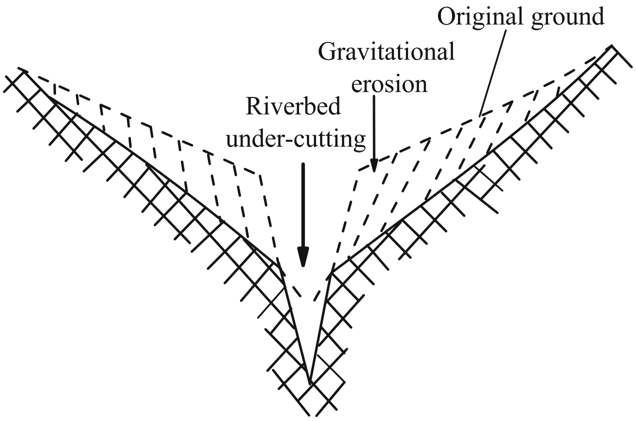

Fig. 377.4 The schematic map of headward erosion in Lamaxi Gully

called the gravitational erosion, which broadens the gully width. For Lamaxi Gully, the hydraulic erosion constantly makes the valley deeper. Vice versa, the deep gully provides conditions for gravitational erosion. Therefore, the mutual effects of hydraulic erosion and gravitational erosion cut the Lamaxi Gully deeper and wider, eventually evolves to the headward erosion phenomenon. The evolution process is schematic illustrated in Fig. 377.4. The influence factors of headward erosion in Lamaxi Gully are as follows:

(1) Rainfall discharge. As the rainwater easily forms gathering surface water to erode Xigeda strata, the rainfall discharge controls the erosion capacity.
(2) Geomorphology. The average primary longitudinal grade of the Lamaxi Gully is 140 %. The slope angles of both sides are about 30–40° with some steep slope ~60°. The geomorphology has influence on the flow path and gravitational potential energy.
(3) Rock mechanic property. The Xigeda rocks with poor engineering and mechanic property are easy to disintegration and expansion when reacting with water.
(4) Water-rock interaction. The water-rock interactions including physical and chemical reactions proceed in the whole weathering and evolution process of the Lamaxi Gully. This factor alters the rock compositions and fractures in the micro-scale.

377.6 Conclusions

Based on the mineralogical, chemical and physical properties of Xigeda rocks in Lamaxi Gully, some conclusions can be drawn:

(1) The Xigeda rocks mainly consist of quartz, albite, K-feldspar, calcite, dolomite, and secondary minerals, which is reflected on the chemical constituents with high content SiO_2 and Al_2O_3.
(2) The particle size, mineral composition and chemical composition of Xigeda rocks, as the internal factors, have significant influence on the development of the headward erosion in Lamaxi Gully.
(3) The headward erosion of Lamaxi Gully is manifested in the hydraulic erosion and gravitational erosion. The eroded model not only erodes the gully from the downstream to upstream, but also broadens the gully width. The geological disasters caused by headward erosion influences the stability of gully.

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References

Bucher K, Zhu Y, Stober I (2009) Groundwater in fractured crystalline rock, the Clara mine, Black Forest, Germany. Int J Earth Sci 98:1727–1739

Corteel C, Dini A, Deyhle A (2005) Element and isotope mobility during water-rock interaction processes. Phys Chem Earth 30:993–996

Gao FF, Wu XY, Deng R (2009) Influence of rock-soil characteristics of Xigeda strata on retrogressive erosion. J Geol Hazards Environ Preserv 20:80–84 (In Chinese with English Abstract)

Göb S, Loges A, Nolde N et al (2013) Major and trace element compositions (including REE) of mineral, thermal, mine and surface waters in SW Germany and implications for water-rock interaction. Appl Geochem 33:127–152

Hao G, Wang W (2010) Effect of content of mud rock on intensity index of Xigeda filling in road subgrade. J Chang'an Univ (Nat Sci Edn) 30(2):53–57 (In Chinese with English Abstract)

Huang SL, Wu XY, Deng R (2010) Study on water-rock interaction in Xigeda strata in Lamaxigou. Subgrade Eng 1:151–153 (In Chinese with English Abstract)

McLennan SM (1993) Weathering and global denudation. J Geol 101:295–303

Newman J, Mitra G (1993) Lateral variations in mylonite zone thickness as influenced by fluid-rock interactions, Linville Falls fault, North-Carolina. J Struct Geol 15:849–863

Ye H, Shi JS, Wang GL et al (2006) Effect of chemical compositions of pisha sandstone on the gravity erosion. Hydrogeol Eng Geol 6:5–9 (In Chinese with English Abstract)

Zulauf G, Palm S, Petschick R, Spies O (1999) Element mobility and volumetric strain in brittle and brittle-viscous shear zones of the superdeep well KTB (Germany). Chem Geol 156:135–149