

Paleo-weathering zone of Cretaceous red mudstone underlying Quaternary loess deposit: a case study on a typical profile

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Present study consists the engineering geological properties and weathered texture of a typical paleo-weathered crust of Cretaceous red mudstone in Lanzhou, Gansu province, China, focusing on the unconformity on its superface. Field hardness and magnetic susceptibility tests in addition to scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were conducted to examine the weathering degree of the zoning of the crust profile. The degree of the paleo-weathered red mudstone can be relatively classified into four distinct zones. The paleo-weathered crust has distinct degrees of vertical zones, with the rock becoming more fragile as weathering degree increases, and the slaking is positively related to the weathering degree.

[Keywords: Red mudstone, Paleo-weathering; Hardness; Slaking; Magnetic susceptibility; Landslide]

Introduction

Lanzhou is located at the western region of the Longxi Loess Plateau, a transitional area between the Qinghai-Tibet Plateau and the Loess Plateau. It has a complicated geological structure and experiences frequent neotectonic movement with geological disasters such as landslides, collapses, and mudflows. In particular, landslides of loess-red beds occur in the western part of Xiliugou area, Nanshan of Xigu district, Gaolan mountain area, etc¹. Cretaceous and Tertiary red beds, which comprise red clastic sedimentary rock containing rich iron oxides, are widely distributed in the urban and the surrounding areas of Lanzhou². Red beds have poor physico-mechanical properties in their natural condition, and their structure easily breaks down through water infiltration and weathering erosion. Quaternary loess deposits cover the red beds and form the “double heterogeneous” slope structure, in which loess on the upper side is loosely textured and porous, while red mudstone at the base has low permeability. In addition, a paleo-weathering crust formed between the red bed and the loess deposits; it is a special form of unconformity; this geologically weak plane plays an important role in the stability or failure of the slope,

creating serious engineering geological problems^{3,4&5}. Many loess-red bed landslides occurred due to a slip zone formed on the superface of or near the paleo-weathering crust^{6&7}. For instance, the Caowang, Banshan, and Yanpucun landslides in Tianshui area, the Chuankou and Laobao landslides in Tongchuan³, and the Baitouyao landslide in Baoji⁸ are related to the paleo-weathering crust, and all caused great losses of human lives and economy.

Recently, many researchers have made achievements on failure and sliding mechanism, and the deformation pattern of weak intercalations during loess-red bed landslides. Li and Miao² analyzed the sliding of loess-red bed landslides and reported that infiltration of surface water weakened the structure of the red bed to form a failure plane, leading to the landslides. Wu et al.³ determined the mechanical mode of deformation and failure of the loess-red bed contact and proposed the contact provided favorable conditions for the generation of landslides under certain conditions. Wen et al.⁵ studied the deformation characteristics of a loess-red bed landslide and suggested that the physico-mechanical properties of the paleo-weathering layer were an important factor controlling the occurrence of the landslide. Li⁹

proposed a landslide classification scheme according to material composition and structural characteristics, and defined landslides where overlying loess and slope diluvium slide along the surface of weathering bedrock as weathering crust landslide. Zhang and Liu¹⁰ analyzed the controlling factors of loess landslides in western China and reported that the paleo-weathering layer significantly affected the location of failure surface. Although previous works indicated that the rock surface by paleo-weathering and erosion was severely fragmented, loose, and even earth-like, it became smooth on contact with water and easily facilitated sliding. However, quantitative descriptions on thickness and development mechanisms of the underlying weathering crust have rarely been reported. Ding and Li¹ investigated two bedding landslides in Gaolan mountain, Lanzhou city, and found that an ancient erosion surface was the main structure controlling the occurrence of the landslides; this layer suffered strong paleo-weathering and was almost 20–30 m in thickness. Qu and Zhang⁴ discussed the effects of soil structure on landslide occurrence and reported that engineering properties and distribution patterns of a paleo-weathering zone in hipparion laterite affected the stability of loess slope; the red earth-like weathering crust of 0.5–1.0 m thickness was found throughout the ancient erosion plane. Zhou¹¹ investigated the Wenchangge landslide in Lanzhou and proposed that its occurrence was strongly correlated to the underlying weathering layer of Cretaceous mudstone (2–3m thick). Mu *et al.*¹² determined the structure of a rockmass during the Shixiakou landslide in Lanzhou city; the upper part was loess while the lower part was extensively weathered Precambrian metamorphic rock (7–9m). During the Jiaoshuwan landslide in Tianshui city, an earthy weathering crust of nearly 1m thick was found

on top of the bedrock¹³. Thus far, no systematic studies of the paleo-weathering crust have been reported. Therefore, investigating engineering properties and structural characteristics is a vital approach towards understanding the formation mechanism of red bed-related loess landslides.

In this study, we investigated a typical paleo-weathering profile of the Cretaceous red mudstone and collected samples systematically, aiming at studying the zoning characteristics of the paleo-weathering zone of red mudstone. To this end, we performed several efficient macro and micro experiments: 1) field hardness test; 2) magnetic susceptibility test; 3) slaking experiment under soaked condition; 4) scanning electron microscopy (SEM); 5) and X-ray diffraction test (XRD).

Materials and Methods

The study area is the IV terrace of the Yellow River, its lithological stratigraphic sequence from new to old is as follows (Fig. 1).

- a) Aeolian Loess of upper Pleistocene (Q_3): generally homogeneous grayish yellow Malan loess with loose pores, dominated by silt (approximately 25–45 m thick).
- b) Alluvium of middle Pleistocene (Q_2): alluvial silty clay (bordeaux or lateritious with a rather dense structure of around 4–17 m thick) and fluvial sandy gravels (approximately 2–5 m thick).
- c) Hekou series of Cretaceous (K): mainly burgundy–darkred mudstone, sandy mudstone and muddy sandstone.

The sampling profile is a paleo-weathering crust of Cretaceous red mudstone, which lies at the north-eastern edge of the Heifangtai area (Fig.1). Sampling



Fig. 1 — Lithological stratigraphic sequence and paleo-weathering profile of Cretaceous red-bed mudstone

was conducted in the burgundy mudstone of 1m range (sampling interval of 10cm) beneath the gravels and the bedrock (unconformity); the rock stratum had an inclination of 82° and dip angle of 12°. The surface of the paleo-weathering profile suffered strong weathering; loose materials (about 15cm thick) were cleaned before the field test and sampling, and the fresh surface was smoothened. Each section was tested and 10 rock samples were collected, and then several experiments were carried out.

Hardness is an efficient index that reflects weathering degree^{14&15}. The hardness of the paleo-weathering crust was determined using an Equotip Piccolo tester (Piccolo), which has been widely applied in various fields, especially in measuring rock compressive strength on site^{14&16}. Hardness values were obtained through single impact on multipoint (SIMP) and multi-impact on a single point (MISP); SIMP involves single impact on 10 different points at each testing depth and calculating the average hardness value as L_a ; MISP involves repeated impact on a single point at each testing depth (the repeat impact was set 20 times) and calculating the average of three maximum hardness values as L_{max} . However, the analysis of L_a and L_{max} only indicates the strength difference of mudstone. To evaluate the weathering degree of rocks, micro-fractures should be considered, which can be reflected by the coefficient of variation¹⁵:

$$k = L_a/L_{max}$$

where k is the coefficient of variation.

The magnetic susceptibility of the paleo-weathering crust of the red mudstone is greatly influenced by paleoclimatic changes; to some degree, it can reveal paleoclimate information about the geological sedimentary age, and paleo-weathering could promote the enrichment of magnetic particles^{17&18}. Magnetic susceptibility is controlled by the concentration of magnetic minerals, which is positively related to weathering degree^{18&19}; hence the weathering degree of red mudstone can be determined by magnetic susceptibility to a certain extent. Multiple measurements of magnetic susceptibility were taken at each depth range using the SM30 Susceptibility Meter. Then the mean value was calculated to represent magnetic variation in the longitudinal direction, and weathering zoning was further analyzed.

The slaking and particle distribution of rocks showed good regularity at different weathering

degrees^{20&21}. Therefore, a slaking experiment was conducted to reveal the slaking property of red mudstone at different depth ranges and regularity was changed along the sampling profile to further reflect variations in weathering degree.

A total of 10 undisturbed red mudstone samples was selected along the profile from top to bottom. Samples were immersed in water after drying and cooling, then slaking was observed and documented, drying and weighing the disintegrations, and finally, the grain size distribution was determined through grading analysis. To study the water-rock effect, electrical conductivity (EC), total dissolved solids (TDS), and pH value of water solutions during the first slaking period were monitored by a portable water quality detecting instrument. As slaking mainly occurred during the first two soaking periods, the experiment was canceled after the second soaked slaking. Slaking form, slaking phenomenon, and grain size distribution was used to analyze the slaking of rock. The major steps of this experiment are as follows.

- (a) Weighing an undisturbed rock sample and placing it on a tray, then drying in an oven at 105 °C for more than 8 h to reach a supreme stable state, and finally weighing the samples after cooling.
- (b) Laying samples on a 2mm-aperture wire netting and hanging the net inside a jar filled with 450 ml water, immersing the samples completely.
- (c) Recording the time-consumed during initial slaking, documenting slaking form, period, and phenomenon after soaking samples for 5 min, 10 min, 30 min, 1 h, 2 h, and 3 h, simultaneously, recording the EC, TDS, and pH of the solution during slaking.
- (d) Drying residues on the wire netting and after 24 h subsidence, and then repeating drying and cooling and screening (a standard screen with pore sizes of 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.1 mm and 0.075 mm was used).
- (e) Placing grains of >2 mm on the wire netting, conducting the second slaking, and then observing and recording the slaking period and phenomenon after soaking samples for 5 min, 10 min, 20 min, 1 h, 2 h, 3 h, and 24 h.
- (f) Soaking rock grains of <2 mm in a bowl for >24 h, and then drying, cooling, weighing, and screening.

SEM is important to the study of rock and soil microstructures and has been widely applied in many

other fields. Extracting microscopic pore parameters by processing and analyzing SEM images contributes to the understanding of the physical properties and microstructure characteristics of rocks and soils²². The test was conducted using the JSM-5600LV Scanning Electron Microscope at the Institute of Physics and Chemistry, Chinese Academy of Sciences. Samples were air-dried to eliminate moisture while maintaining the natural structure. All samples were observed under SEM after coating to improve image quality while avoiding thermal damage. Images were amplified from 50× to 5000×, containing medium-micro ($A < 200$, A is the amplification), microscopic ($200 < A < 1000$) and optico-microscopic ($A > 1000$) images, providing various microstructure information²³. Three to five SEM images were taken at the same magnification factor.

XRD is important in determining mineral composition analyzing mineral crystal structure. The paleo-weathering crusts contain several clay minerals and their combinations, variations in content, and structural features are important in speculating the origin and climatic characteristics of the crusts²⁴. Additionally, the aggregation type and mechanical properties of clay minerals are important to engineering construction and geological hazards research. XRD of clay minerals was mainly conducted using X'Pert Pro MPD, and data processed using MDI Jade 5.0. Samples were ground into powders with an agate mortar and pestle. The agate mortar was cleaned using suitable cleaning materials: distilled water, silica analytical reagent, disilicon trioxide analytical reagent, and ethylene glycol. Then clay was extracted and processed from the oriented samples in three ways: 1) air-drying; 2) saturation with ethylene glycol; and 3) heating to 550°C for 2 h.

Results

As shown in Figure 2, the average value of SIMP (L_a ranges 164.3–365.6) and the maximum average value of MISP (L_{max} ranges 264.1–561.7) share a similar changing pattern along the profile from top to bottom, increasing with depth. It also shows that the strength of red mudstone continuously increases with depth. The curve exhibits an upward trend except for a slight decrease at 20–30 cm and 90–100 cm. Two valley points emerge in the curve of hardness coefficient of variation (k , Fig. 3): the first is 0.64 at 40–50 cm with uprush to 0.74 at 50–60 cm; and the second is 0.65 at 80–90 cm, but 0.74 at 70–80 cm. L_a and L_{max} both reach the maximum at 80–90 cm

depth where the strength of mudstone is rather strong. A steep decline in this depth range may indicate that large fractures exist near the testing point. The coefficient of variation fluctuated with a narrow range at 0–50 cm depth below the gravels, and can be classified into 0–30 cm and 30–50 cm according to the fluctuation pattern. Based on the hardness coefficient of variation, strength zoning of the profile can be generally classified into three zones: 0–30 cm, 30–50 cm, and 50–100 cm. As shown in Figure 4, the maximum magnetic susceptibility is 0.209×10^{-3} at the surface of the profile, which suggests that the superficial layer of the paleo-weathering crust suffered strong weathering. Within the testing depth range, magnetic susceptibility presented a four-stage variation and two valleys appeared, which are 0.155×10^{-3} at 20–30 cm and 0.118 at 80–90 cm. The cut-off points of magnetic susceptibility are 30 cm, 60 cm, and 90 cm beneath the gravels.

The initial slaking time is presented in Table 1, and Table 2 briefly summarizes the phenomenon during two soaked slaking periods.

The slaking of rock samples varied with different depth ranges. During the first soaked slaking, the

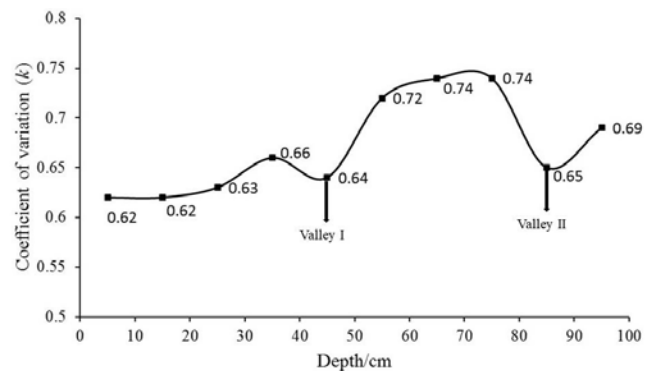


Fig. 2 — Curve of changes in hardness

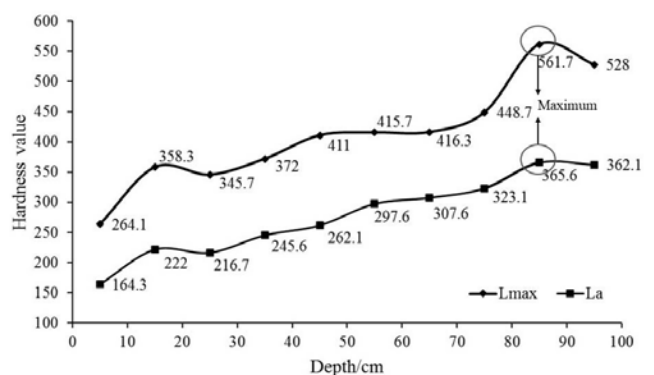


Fig. 3 — Curve of the coefficient of variation of hardness

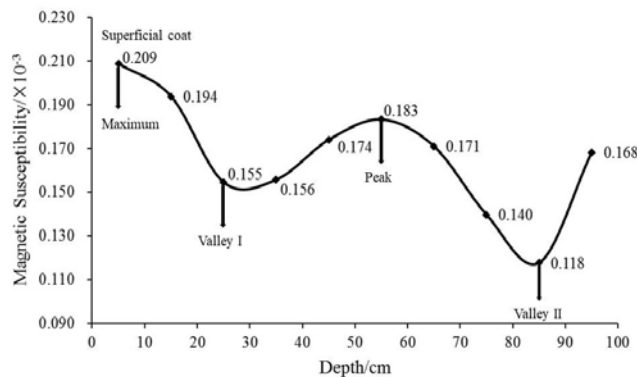


Fig. 4 — Curve of changes in magnetic susceptibility

occurrence of slaking, air bubbles, fractures, slaking forms, and the form and amount of residues were macro evaluation signals to observe the slaking of rock samples. Slaking slowed down with depth, observed from the delayed occurrence of initial slaking, fewer air bubbles, slow generation of fractures, increased residue on the wire netting, and disintegration of rock samples transitioning from muddy, plate-shaped, and granular to coarsely granular, bulky, and fragmental forms. At 0–30 cm depth, slaking was very fast, and all samples were almost loosely amassed in 30 min; at 30–60 cm depth, slaking was quite fast but comparatively slower, and

Table 1 — Initial slaking time of red bed mudstone samples

Depth/cm	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Initial Time/s	1	2	3	5	5	5	10	10	10	12

Table 2 — Slaking phenomenon of red bed mudstone samples under soaking

Depth/cm	First slaking	Second slaking
0–10	Slaking occurred immediately after immersion and many air bubbles formed. Rock samples almost disintegrated in 5 min, and slaking forms were granular, muddy, flaky, and bulky; completely loose after 30 min, but no distinct phenomenon afterward.	Very fast slaking, bulky rocks disintegrated into granules and even powder; air bubbles continuously formed after 5 min but the amount decreased; few rock residues remained on the wire netting at 10 min; after 30 min, slaking was completed.
30–40	Fast slaking, disintegrated into 2 parts along the fracture generated from the surface; only a large rock mass left in 5 min, and slaking forms were mainly flaky and granular; no air bubbles formed at 10 min; fracture generated on the residual rock in 30 min, but no obvious phenomenon afterward.	Very fast slaking, a large amount of small air bubbles formed and but none at 10 min, the large rock mass split and there remained little residues on the wire netting; no distinguished slaking was observed in 30 min; an obvious variation after 24 h. The overall slaking pace was slower.
50–60	Fast slaking accompanied by numerous air bubbles; a single large rock was noticed in 5 min, and forms were mainly granular, plate-shaped, and needle-shaped; no slaking was observed after 30 min and later.	Rather fast slaking associated with generous small air bubbles; forms were mainly plate-shaped and granular at 5 min; little residues on the wire netting; no obvious changes in 30 min; residue on the netting slightly reduced at 24 h.
60–70	Slaking was becoming relatively slow, only a few air bubbles formed, and fracture emerged in 1 min; bulky slaking in 2 min; fragmental rocks accumulated on the netting; no slaking in 30 min.	Fast slaking with numerous small bubbles, fracture occurred on the surface of large rock mass, and forms were mainly granular and plate-shaped with small fragments.
70–80	Few air bubbles formed, and granular slaking was not distinct; multi fractures generated on the surface in 30 min, bulky rock mass collapsed, and forms were mainly bulky and granular; rock mass was intact at 1 h and no obvious change later.	Numerous air bubbles formed instantly, rock particles continuously collapsed from the large rock body and disintegrated into four parts in 5 min; loosely accumulated on the netting in 10 min, remained rather large rocks, and only partial rock mass left in 30 min with no distinct variation afterward.
80–90	Few large air bubbles formed and slaking was not obvious; a fracture developed in 90 s, two fractures in 5 min, and rock was disintegrated into three parts; afterward fracture increased continuously, forms were mainly coarsely granular and fragmental; no obvious changes in 30 min.	Numerous air bubbles formed and fragmental rocks quickly disintegrated into granular; only two rather large rocks remained after 1 min; bulky and granular in 5 min; residues decreased in 30 min; minor reduction in 24 h, and forms were mainly coarsely granular and small fragments.
90–100	Very few air bubbles formed and slaking was not obvious; no bubbles in 5 min; a horizontal fracture generated in 1 h; residues slightly reduced at 3 h, no other phenomenon was observed, and slaking pace was extremely slow.	Slow slaking associated with air bubble generation, large plate-shaped rock disintegrated into small and coarse granules; the form of residual rock changed significantly, but still accumulated on the wire netting in large quantity.

small-sized rock masses still remained; at 60–90 cm depth, slaking was relatively slow associated with fewer air bubbles, and fragmental rocks remained at 30 min; at 90–100 cm depth, slaking was not obvious, and no other phenomenon appeared except for a horizontal fracture. The second soaked slaking was faster and more intense than the first one; air bubbles still appeared, and more fractures developed at an accelerating speed. During both soaked slaking periods, the speed and extent of slaking decreased with increasing depth.

The grain size distribution of red mudstone after two soaked slaking periods is illustrated in Figure 5. Each size fraction exhibited a certain regularity from the top of the profile to the bottom. As the first soaked slaking period accomplished, grains of less than 0.1 mm were nearly evenly distributed throughout the testing depth range and accounted for a maximum of 4.01% of all grains. Grain of sizes 0.1–0.25 mm showed minor variations but constituted a small proportion. However, grains of sizes 0.25–0.5 mm accounted for more than 10% at depths of 0–60 cm, but the maximum proportion was only 6.79% at depths of 60–100 cm. Further, there was a steep drop in proportion from the 50–60 cm depth range to the 60–70 cm depth range. Grains of sizes 0.5–1 mm were more concentrated in the upper 0–60 cm than the bottom. At depths of 0–60 cm, the proportion of these

grains reached a maximum of 29.55% and a minimum of 18.23%; the corresponding values for the 60–100 cm depth range were 11.35% and 6.59%. Grains of sizes 1–2 mm presented a similar distribution pattern, while 2–5 mm sized grains displayed the opposite pattern. At depths of 0–60 cm, 0.5–5 mm sized coarse grains were dominant. However, at depths of 60–100 cm, 2–5 mm sized coarse grains comprised more than a half of the particles. Therefore, based on the overall grain size distribution, a downward coarsening trend was displayed along the profile. On opposite sides of the 60 cm depth mark, the grain size distribution showed marked variation, which could be closely related to the degree of weathering.

Once the second soaked slaking completed, the grain size distribution of red mudstone changed remarkably. An exception to this was the depth range of 90–100 cm, for which only a minor variation occurred between the two soaked slaking periods. Although the 2–5 mm sized grains reduced, they still comprised 60.70% of the total. At depths of 0–30 cm, 1–5 mm sized grains sharply decreased, but the grain size distribution of the three included depth range sections was similar. At depths of 30–60 cm, the distribution was very closed within the three included depth range sections. But the distribution still showed great diversity between the depth of 50–60 cm to 60–70 cm. From the above data analysis and comparison,

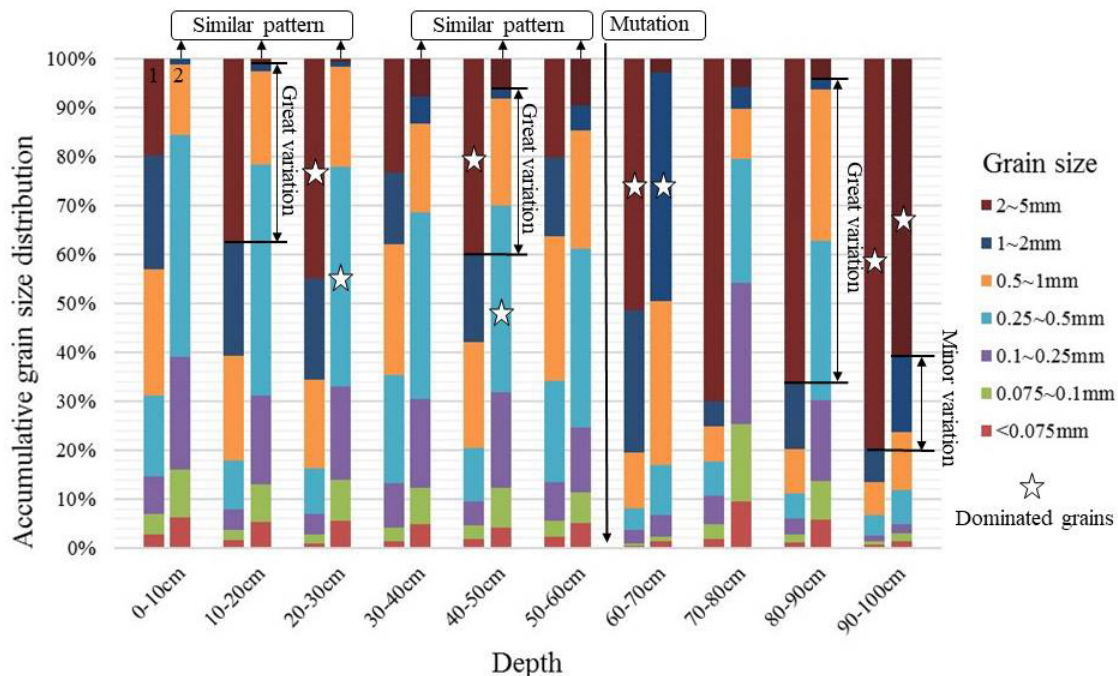


Fig. 5 — The particle distribution of samples in different depth after two separate soaked slaking periods

it is suggested that the 30 cm, 60 cm, and 90 cm depths may be three lithological boundaries. Clearly, 2–5 mm sized grains decreased significantly and 0.1–1 mm sized grains were dominant at depths of 0–90 cm. Grains of sizes 0.1–0.5 mm, and in particular 0.25–0.5 mm sized grains, increased greatly at depths of 0–60 cm. Meanwhile, 0.1–0.5 mm sized grains also significantly increased at depths of 70–90 cm. The grain size of the remaining two depth sections (60–70 cm and 90–100 cm) both showed an increase, except for the 2–5 mm size fraction, which decreased. Hence, our data indicate that the slaking of rocks was also the process of fragmentation and refining of coarse grains.

Based on the slaking phenomenon and grain size distribution, the paleo-weathering crust profile of red mudstone could be classified into four zones: 0–30 cm, 30–60 cm, 60–90 cm, and 90–100 cm.

Discussion

Slaking is an efficient index to reveal the physico-mechanical properties of rocks. Analysis of the slaking mechanism can provide valuable information for the prevention of geological engineering problems and the protection of rock slopes. Based on the grain size distribution and slaking phenomenon, we have divided the sampling profile into four zones. It is clear that the anti-slaking tendency increases downward; thus, there are also four slaking zones of different degrees. Extremely strong slaking characterizes the 0–30 cm zone, strong slaking is seen in the 30–60 cm zone, weak slaking occurs in the 60–90 cm zone and weaker slaking occurs in the 90–100 cm zone. This suggests that slaking shows a

vertical zoning along the paleo-weathering crust, which may have indications for the illustration of its weathering features.

The SEM images of undisturbed rock samples and the slaking forms were used to reveal the connection between microstructures and macro slaking as well as to find out the micro changing pattern. The slaking of red mudstone mainly occurred as granular, muddy, plate-shaped, bulky, fragmental and occasionally needle-shaped. The SEM images (Fig. 6) of undisturbed rock samples provided abundant information about microstructure, and three typical SEM images from different depths are displayed. The phenomenon of aggregation of a large number of fine clastic particles into clusters was manifested in all rock samples but to varying degrees. The microstructures are mainly granular, plate-shaped, fragmental, and bulky in different densification. The upper part of the profile is dominated by fine grains and a few plate-shaped grains with good roundness (Fig. 6a), whereas the lower part is dominated by coarse-grained, fragmental, massive downwards. Distinct edges and corners are seen, and a large number of voids and micro fractures are developed, while a tensile fracture can be partially seen [Fig. 6 (b and c)]. As a whole, the particle aggregation size increases gradually downward, and the microstructure also increases in density. Based on the slaking form of the corresponding rock sample, the slaking form of the rock sample is the macro scale expression of its microstructure. Moreover, the fractures generated on the surface are also the macro scale expression of the tension micro-fractures. Furthermore, the fracture generation and amount are inversely related to the anti-slaking capacity.

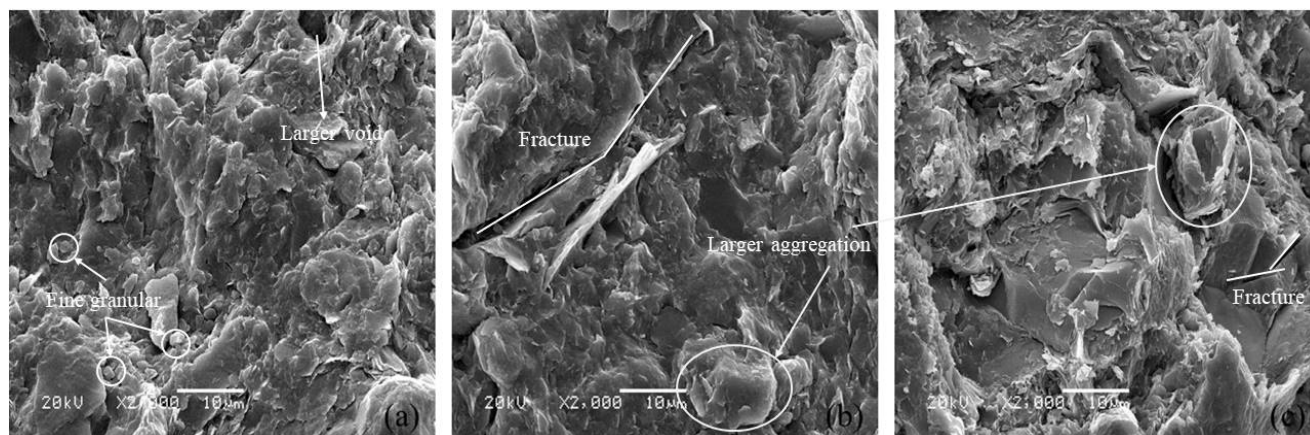


Fig. 6 — The SEM images of undisturbed samples: (a) represents depth of 0–10 cm, (b) represents depth of 30–40 cm, (c) represents depth of 70–80 cm

XRD analysis revealed the clay mineral composition of the paleo-weathering crust of red mudstone, which is 12.7% kaolinite, 47.0% illite, and a mixed illite/montmorillonite layer accounting for 40.3%. All components are fine-grained and possess a strong-hydrophilic property. Montmorillonite and illite could cause the soft rock to swell on encountering water^{25&26}. In this case, the volume of montmorillonite will increase by 50–60% of its original volume, while that of illite will increase 10–30 times^{27&28}. During the first soaked slaking, the surface of rock samples is easily fractured and disintegrates in a short time. The muddy structure and clay mineral cement were damaged seriously, and coarse grains disintegrated into fine grains. When the drying red mudstone encountered water, the hydrophilic clay minerals swelled. Meanwhile, microvoids were refilled with water and micro-fractures increased in number, which caused the formation of new weak planes, thereby destroying the internal structure. Soluble salts dissolved gradually, and the cementation consequently decayed because cements were softened and dissolved, which further caused a reduction in the strength of joints between particles, eventually resulting in disintegration. In the two soaked slaking cycles, soft rock samples suffered dehydration, water absorption, swelling, followed by a second episode of dehydration and water absorption. As a result, the soft rock suffered damage, and subsequently, voids and fractures increased and broadened: therefore, the slaking accelerated during the second soaked slaking and produced more air bubbles. Though soaked slaking of red mudstone was conducted under no limited boundary condition, it still reflected the strong water sensitivity of red mudstone. Generally speaking, red mudstone is easily disintegrated upon encountering water because of its microstructural features and clay mineral composition.

Several macro and micro indexes were acquired and analyzed through a set of integrated experiments to evaluate the weathering of the paleo-weathering crust of Cretaceous red mudstone. Hardness, magnetic susceptibility, slaking, microstructural features, and clay mineral compositions were synthetically used to achieve the weathering zonation. The hardness index showed that rock strength increased downward along the profile, yet it could not precisely determine the weathering degree. At depths of 0–30 cm, the hardness coefficient of varied in the range 0.62–0.63,

which is the minimum in the entire testing range; moreover, the anti-slaking property in this depth range is also the weakest. The magnetic susceptibility reached a peak at depths of 0–20 cm but dropped to a valley at depths of 20–30 cm. This occurs mainly as a result of the strong weathering on the surface layer and soil formation process. The soil formation process advanced the enrichment of iron magnetic particles¹⁷. As aforementioned, the 30cm depth below the gravels was supposed to be an interface between two different weathering zones.

Figure 1 shows a horizontal crack 60 cm below the gravels. This is also where the magnetic susceptibility reached its peak value in the depth range of 30–90 cm. The chemical properties of water solution during the first slaking period are presented in Figure 7. EC (Fig. 7a) and TDS (Fig. 7b) of samples from depths of 40–60 cm and 90–100 cm is larger than those of the other depth ranges, and both reached a maximum at the depth range of 50–60cm. This is due to the long-term irrigation of the overlying loess, which causes the gradual saturation of the loess as well as the raising of the groundwater table. Some soluble salts found in loess were dissolved in groundwater and migrated to the top of the red mudstone through joints and cracks of the silty clay. However, due to the serious weathering of the 0–30 cm depth zone below the gravels, groundwater infiltrated directly downward and dissolved salts were held inside the red mudstone. Below the depth of 60cm, the rock was solidifying and the seepage channels had decreased; thus, a majority of salts remained in the depth range of 50–60 cm. However, a lower salt content distribution was observed in the neighboring depth ranges of 40–50 cm and 60–70 cm. Additionally, there was a great difference between the 60–70cm and 50–60 cm depth sections after soaked slaking. In summary, the 60 cm depth below the gravels is a weathering interface. The grain size distribution of rock samples from depths of 90–100 cm had obvious distinctions from other samples, and the anti-slaking property of these samples was the strongest, which indicated the weakest weathering.

The paleo-weathering crust of red mudstone lies underneath the Quaternary stratum, which means that the sedimentary and age of formation is rather new. It is not only affected by paleo-weathering, but also by modern weathering, especially the effect of groundwater, which complicates its engineering geological properties. SEM images indicate that the

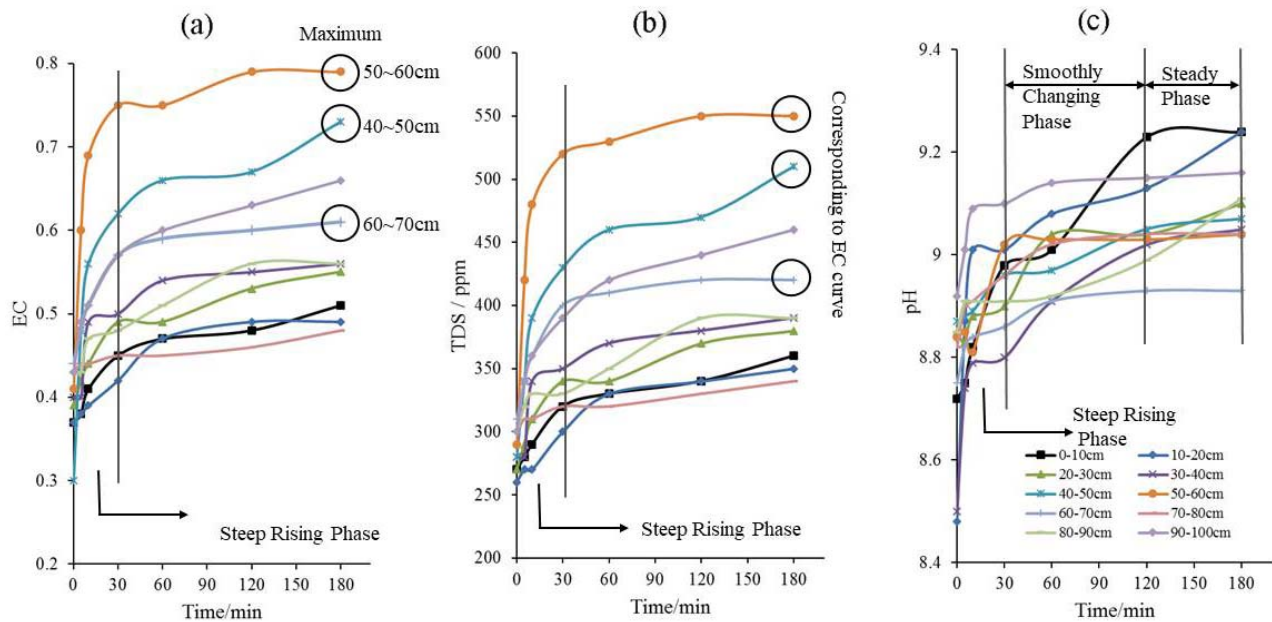


Fig. 7 — Variations of chemical properties of water solution: (a) is the changing curve of electronic conductivity, (b) is the changing curve of TDS value, (c) is the changing curve of pH value

rock structure becomes more solid downwards. The structure would be damaged once it underwent the weathering process, with the micro-scale processes being the fragmentation and refinement of grains. Therefore, weathering had a greater impact on the upper part of the profile than on the lower part. Above all, four weathering zones can be determined by systematically analyzing multiple micro and macro factors: a strong weathering zone at 0–30 cm, a moderate weathering zone at 30–60 cm, a zone of weak weathering at 60–90 cm, and a zone of slight weathering at 90–100 cm. The paleo-weathering profile showed obvious vertical weathering zoning from the top to the bottom.

From the detailed information gained from the above analysis, we have systematically investigated the weathering zoning and engineering geological properties of the paleo-weathering crust of red mudstone. The TDS, EC, and pH values all basically stabilized in 2 h during slaking (Fig. 7), which indicated the fast dissolution of internal salts of the red mudstone. At depths of 0–30 cm, the mudstone was extensively weathered and also exhibited an extremely strong slaking property; the salts dissolved easily and migrated by infiltration of groundwater within the loess stratum. However, the water solution was alkaline (Fig. 6c). The strengthening of alkalinity could accelerate the dissolution of clay mineral cements and further speed up the strength reduction



Fig. 8 — An exposed spring nearby

of the rock samples²⁹. Relatively speaking, although red mudstone of other depth sections exhibits weaker experimental results agree with the field investigations. Generally, spring seepage occurs along weathering and a weaker slaking property, cement dissolution is still active during water infiltration. The the edge of the tableland including loess, gravels and Cretaceous red mudstone, where large amounts of salts are precipitated (Fig. 8). It demonstrated the result gained by chemical analysis of water solution that the rock mass contained a large quantity of salts. The irrigation water infiltrated into the red mudstone and caused the rising of the groundwater table, finally emerging at a different location with high TDS. In the process of salt dissolution and loss, the red mudstone underwent softening in varying degrees, and coupled

with the effect of weathering in different zones, the instability of the slope increased and significantly raised the chances of landslide and mudflow occurrence. This theory may be able to explain the work of Wu *et al.*³ on dozens of red bed landslides in loess areas. They believed that water is an important external factor that induced landslides and discovered that all sliding planes were generated along the contact between loess and the underlying red bed. Both water and the paleo-weathering crust had a significant impact on slope stability.

The paleo-weathering crust profile of Cretaceous red mudstone in this study is river-terraced. It displays a zoned weathering structure and exhibits physico-chemical properties that provide plenty valuable information about the formation mechanism of loess-red bed landslides. In particular, paleo-weathering crusts of various lithologies in different landscapes should be discussed in further research along with their clean-out effect on landslides.

Conclusion

On the basis of micro and macro experiments, the following conclusions can be drawn.

- (a) The paleo-weathering crust presented distinct vertical weathering zoning characteristics. It has been modified by paleo-weathering and is still undergoing modern weathering, especially by water infiltration. The profile could be divided into four weathering zones from the top to the bottom, namely, an extensively weathered zone, a moderately weathered zone, a weakly weathered zone, and a slightly weathered zone.
- (b) Red mudstone exhibits a strong slaking capacity, with its microstructure and clay mineral composition being the two main factors that affect this property.
- (c) Loess areas, where the red bed is well distributed, the infiltration of irrigation water caused the loss of salts and the weakening of the red mudstone cement. This resulted in rock strength reduction, which increased the instability of slopes in the red bed area. Irrigation should be restricted and more precautions should be taken to reduce the damage that surface water infiltration brings to slopes in red bed areas.

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