Environ Earth Sci (2015) 73:1161–1167
DOI 10.1007/s12665-014-3469-1

ORIGINAL ARTICLE

Effect of Quaternary climatic change on modern hydrological systems in the southern Chinese Loess Plateau

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Received: 26 November 2012 / Accepted: 18 June 2014 / Published online: 17 July 2014

Abstract A systematic study was conducted to investigate the permeability, porosity, grain size, water content, mass percentage of carbonate, and magnetic susceptibility of representative Middle Pleistocene loess-palaeosol layers (from L1 to S5) on the Chinese Loess Plateau. The average infiltration rate of the loess (0.93 mm/min) was higher than the palaeosol (0.62 mm/min), and the porosity of loess was higher than that of palaeosol. The loess layers have greater water-bearing capacity and, therefore, they are more likely to form aquifers while the palaeosol layers are more prone to form aquitards. The greater permeability and the larger water-bearing space of the loess layers are largely the result of lower intensity pedogenesis due to the colder/drier climatic conditions at the time these sediments were deposited. Conversely, the weaker permeability and lesser water-bearing capacity of the palaeosol layers can be explained by the greater pedogenesis during the warmer/wetter climatic conditions. The studies demonstrate a compelling relationship between Pleistocene climate and modern hydrological systems in the southern Chinese Loess Plateau.

Keywords Loess · Chang'an county · Permeability · Aquifer and aquifuge · Pleistocene climate

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Introduction

Research on loess and the environment has shown that the Chinese loess-palaeosol sequence preserves a detailed record of environmental change and provides a useful reference for comparisons of long-term environmental change (e.g. Liu 1985; Kukla et al. 1988; Ding et al. 1990; An et al. 1991; Sun et al. 1996; Guo et al. 1998; Lu and An 1998; Kohfeld and Harrison 2003; Porter and An 2005; Thomas et al. 2007). Beginning in the 1970s, the groundwater sources and infiltration migration characteristics of loess have been studied in detail, and many important discoveries have been made (e.g. Wang 1982; Yang et al. 1982; Yan and Wang 1983). For example, studies have shown that the groundwater in the voids, fissures, and pores of loess is mainly from atmospheric precipitation (Xue 1995; Yang et al. 1982). Various properties of loess from many regions, including Central Asia (Dodonov 1991; Dodonov and Baiguzina 1995), Europe (Pesci 1997; Kukla 1977) and the United States (Jacobs et al. 1997; Jacobs and Mason 2007), have been studied, but little if any tangible progress has been made relative to the infiltration and migration of water. Some research into the aeration of loess and the flow of groundwater has been conducted, but the loess layers enriched in groundwater have not yet been clearly classified (Xue 1995; Li et al. 1999). To some extent, these difficulties arise from the multitude of factors that affect the movements of water in loess, and as a result research has been challenging.

Loess is distinct from general loose sediments, which are in essence soils (Zhao 1991, 2002; Tang and He 2002). Soil water and groundwater in loess have a particular configuration; that is, they typically occur in multiple layers, even forming small-scale groundwater pools in aerated zones. Previous studies of groundwater in Chinese

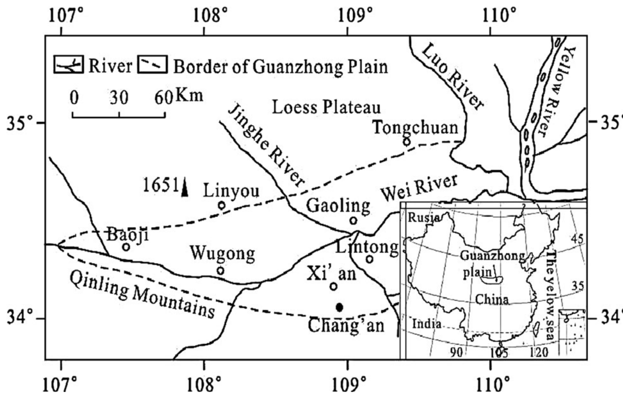

Fig. 1 Study area and its location in China

loess have resolved some issues including the sources, migration, and storage capacity of water in aerated loess layers. However, other hydrological issues in loess sections have received little attention; these include the identification of specific layers of groundwater enrichment, the principles governing groundwater enrichment, the development and degree of water-bearing spaces, the formation of aquifers and aquifuges, and the relationships among the various hydrological characteristics and climate change, etc. Thus, there are compelling reasons for understanding the relationships between soil water and groundwater in loess deposits.

This article presents the results of a series of experiments designed to investigate the hydrological properties of loess and palaeosol and the differences between them. The data were used to establish relationships between Quaternary climatic change and modern hydrological systems. The study builds on the fact that changes in palaeoclimate controlled the layering of the loess-palaeosol sequences, and the resulting differences in the texture and structure of the sedimentary layers affect the hydrology of modern soils. Understanding these connections is significant for studies of soil water content and groundwater enrichment, and this knowledge is highly relevant for water resource development and utilisation. In this regard, climatic change theory can be applied to issues of water resource conservation in the Chinese Loess Plateau area, and this work extends applications of climate change theory in the Quaternary period.

Materials and methods

Study area

Shaoling Yuan (i.e. the loess tableland) was chosen as a study area for the project (Fig. 1); it is in the heartland of Guanzhong plain, with the Qinling Mountains to the south and the Xi'an to the north. The regional climate is classified as a warm temperate, semi-humid, continental monsoon; the annual mean temperature is ~13.1 °C and the annual precipitation is ~700 mm. The major soil type is drab soil; the other type is loessial soil (Dodonov 1991) developed under the influence of tillage of parent material. This area has little natural vegetation and is primarily farmland. The water resources available in this area are only about 1/7 of the national average. Owing to the influence of the various geological structures in this area, the differences in groundwater levels and water-yield properties are quite large. In the western plain, groundwater is shallow and the water yield abundant while in the eastern tableland the water yields are poorer (Chang'an County local records compilation Committee 1999).

Table 1 Thickness of strata from L1 to S5 at Shuangzhu in Chang'an

Soil layer	L1	S1	L2	S2	L3	S3	L4	S4	L5	S5
Thickness (m)	6.0	2.1	3.7	2.2	3.3	2.3	4.7	1.4	3.2	4.5

The research site was established at a loess-palaeosol section (i.e. L1, S1, L2, S2, L3, S3, L4, S4, L5 and S5) near the village of Shuangzhu. The thicknesses of the strata outcrops are shown in Table 1. Previous research conducted on this section indicates that the well-developed loess-palaeosol strata can be considered representative of the southern Chinese Loess Plateau, and the strata from L1 to S5 developed between 10,000 and 500,000 years BP (Liu 1985).

Field survey and laboratory analysis

A double-cylinder permeameter (Li et al. 2006) was used to measure soil permeability. The permeability data were obtained from in situ measurements made on each loess and palaeosol layer. Flat surfaces on the sunless side of a hill were selected for sampling to avoid local evaporation, and a total of ten experimental sites were established. Finally, the height of water-column permeating into the soil with unit time and unit area was used to determine infiltration rates. The following three empirical infiltration formulas (e.g. Kang et al. 1996; Liu and Kang 1998; Wang et al. 2004; Lv and Wu 2008) were used to estimate the infiltration rates [$f(t)$ in mm/min] from the experimental data:

1. The Koctakob formula: $f(t) = at^{-b}$, where t is the infiltration time (min) and a and b are empirical parameters;
2. The Horton formula: $f(t) = f_C + (f_0 - f_C)e^{-kt}$, where f_0 and f_C represent the initial infiltration rate and quasi-steady infiltration rate, respectively, k is an empirical parameter and t is the infiltration time (min);

3. The General formula: $f(t) = a_1 + b_1 t^{-n}$, where t is the infiltration time (min) and the others are empirical parameters.

Adjusted for the thickness of each loess/palaeosol layer, soil samples of porosity and grain size (a total of 80) were collected uniformly from each of the layers. Soil sample ring kits were utilised to obtain samples for porosity analysis, and aluminium specimen boxes were used to collect samples for the analyses of grain size. A standard procedure proposed by the Ministry of Agriculture of China (1993) was chosen to determine the bulk densities of the sample soils; then the soil porosity was calculated (Hu and Yang 1987). Grain size samples were analysed with the use of a particle size measuring system (i.e. a Malvern Mastersizer-2000 system). The information on grain size is presented as volume percentages.

In addition, soil samples of water content, carbonates mass percentage and magnetic susceptibility (a total of 402) were collected from the strata at 25 cm intervals. Soil water contents were determined by weighing the samples before and after drying (Zhao et al. 2002). Carbonate mass percentages were determined with an Eijkelkamp Calcimeter-08.53, and the carbonate mass percentage was obtained by determining the volume of CO_2 that emanated from the system. Magnetic susceptibility was measured with a Bartington MS-2 system. A 10 g soil sample which had been sieved to remove particles >2 mm was fitted into a clean and non-magnetic standard plastic sample container. The magnetic susceptibility information was obtained directly from the analytical instrument.

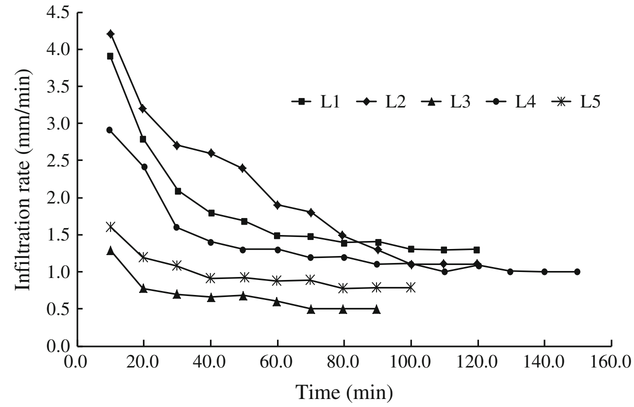

Fig. 2 Infiltration rate for *L1*, *L2*, *L3*, *L4* and *L5* at Shuangzhu in Chang'an

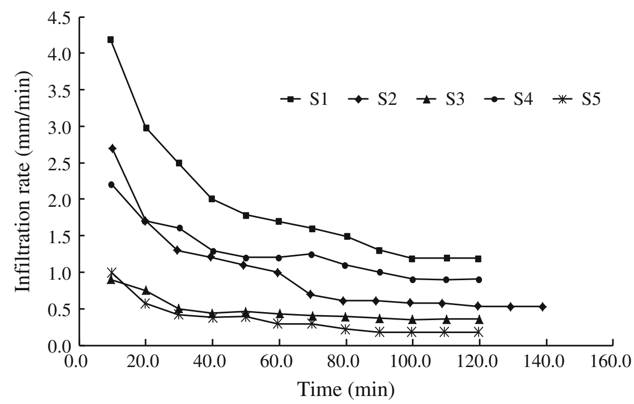

Fig. 3 Infiltration rate for *S1*, *S2*, *S3*, *S4* and *S5* at Shuangzhu in Chang'an

Results and discussion

Infiltration rates and permeability

Li et al. (1999) compared the infiltration rates of different aged loess and palaeosol layers from the Weibei Loess Plateau, and these authors found significant differences in the permeability of the early, middle, and late Pleistocene soil layers. In this loess-palaeosol layer, the infiltration rates varied with time as shown in Figs. 2 and 3. The rate prior to 10 min was taken as the initial infiltration rate. After ~60–80 min, the infiltration rate of the loess layers reached a quasi-steady value (Fig. 2); after ~100–120 min, the infiltration rate of the palaeosol layers reached a quasi-steady value (Fig. 3). Of the loess layers, the initial infiltration rate of L2 was the fastest, and it was followed by L1, L4, L5 and L3; the quasi-steady infiltration rate of L1 was the fastest; it was followed by L2, L4, L5 and L3 (Table 2). For the palaeosol layers, the initial infiltration rate of S1 was the highest and this was followed by S2, S4, S5 and S3; the quasi-steady infiltration rate of S1 was the fastest and it was followed by S4, S2, S3 and S5 (Table 2).

The regression values were all greater than 0.8 indicating that the experimental data are reliable and a reasonable representation of the permeability characteristics of the loess and palaeosols (Table 3). The values of 'b' reflect the relationship between infiltration rates and time. The values of '$(f_0 - f_C)$' reflect the difference between the initial infiltration rate and the quasi-steady infiltration rate. The values of 'a_1' are essentially equivalent to a quasi-steady infiltration rate (Wang et al. 2004; Lv and Wu 2008). These all suggest that the infiltration rate of L4 decreased the fastest with time and S5 decreased the slowest; L2 exhibited the greatest change between the initial infiltration rate and the quasi-steady infiltration rate, and the infiltration rate for L1 is the greatest and S5 is the lowest.

Measurements of the average infiltration rates and quasi-steady infiltration rates, by contrast, showed that both types

Table 2 Initial infiltration rate and quasi-steady infiltration rate from L_1 to S_5 at Shuangzhu in Chang'an

Soil layer	L_1	S_1	L_2	S_2	L_3	S_3	L_4	S_4	L_5	S_5
Initial infiltration rate (mm/min)	3.96	–	4.24	–	1.27	–	3.00	–	1.60	–
	–	4.24	–	2.68	–	0.99	–	2.10	–	1.00
Quasi-steady infiltration rate (mm/min)	1.34	–	1.06	–	0.49	–	0.99	–	0.77	–
	–	1.20	–	0.56	–	0.35	–	0.84	–	0.14

Table 3 Results of regression analysis

Layer	Koctakob formula			Horton formula				General formula			
	a	b	R^2	f_C	$f_0 - f_C$	k	R^2	a_1	b_1	n	R^2
L1	9.94	0.44	0.95	1.34	2.62	0.008	0.74	1.31	221.66	1.75	0.95
S1	14.63	0.53	0.99	1.20	3.04	0.011	0.89	1.20	119.46	1.42	0.83
L2	10.41	0.60	0.99	1.06	3.18	0.013	0.97	1.06	60.90	1.11	0.81
S2	20.75	0.61	0.90	0.56	2.12	0.010	0.87	0.57	83.89	1.43	0.91
L3	2.99	0.41	0.95	0.49	0.78	0.010	0.81	0.50	11.79	1.20	0.96
S3	2.51	0.41	0.96	0.35	0.64	0.009	0.88	0.35	5.34	0.91	0.93
L4	17.12	0.66	0.83	0.99	1.98	0.011	0.72	0.99	58.98	1.35	0.95
S4	5.75	0.21	0.97	0.84	1.27	0.008	0.91	0.85	28.92	1.18	0.85
L5	3.20	0.32	0.97	0.77	0.85	0.007	0.80	0.78	20.96	1.33	0.96
S5	6.80	0.10	0.95	0.14	0.85	0.017	0.92	0.14	9.86	1.40	0.94

R is the correlation coefficient

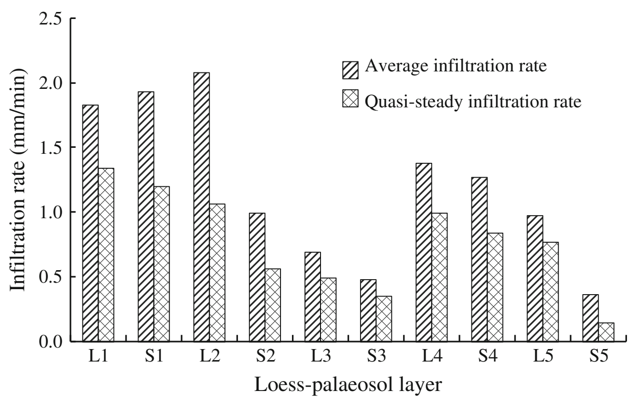

Fig. 4 Average infiltration rate and quasi-steady infiltration rate of soil layers from *L1* to *S5* at Shuangzhu in Chang'an

of sediments exhibit similar downward progressions from L1 to S5 but with some anomalous changes (Fig. 4); most notably that the infiltration rates of L3 and S3 were smaller than in the adjacent layers. Evidently, the infiltration rates of the loess layers were greater than those of the adjacent palaeosol layers; this implied that the loess was more permeable than the palaeosol.

Porosity and grain size and water-bearing space

Water-bearing space was mainly composed of the voids, fissures and holes in loess (Zhao et al. 2002). However, how many pores in soil can be measured by porosity which is an important index for describing it. In this loess-palaeosol section, porosity was measured and the result is shown in Fig. 5. The porosity of the loess layers ranged from 47.85 to 52.10 %, while the palaeosols' porosity ranged from 39.88 to 47.8 % (Fig. 5). Of the loess layers, the porosity of L3 was the highest and L5 was the lowest. For the palaeosols, S1 showed the highest porosity and S5 the lowest. Obviously, the porosity had large differences between the loess and palaeosol layers; especially, the difference between L5 and S5 was 7.97 %.

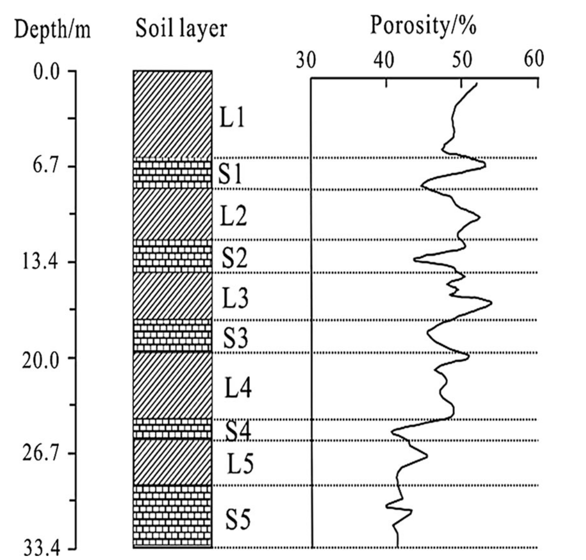

Fig. 5 Porosity of soil layers from *L1* to *S5* at Shuangzhu in Chang'an

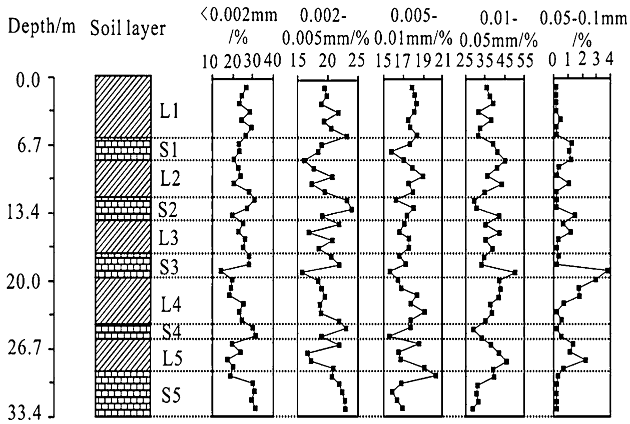

Fig. 6 Grain-size content of soil layers from *L1* to *S5* at Shuangzhu in Chang'an

Xu et al. (2000) carried out studies on the porosity of loess and palaeosol layers, and they concluded that the sediments' grain size was the most important determinant of porosity. In the loess layers, the mass percentage of silt particles varied from 48.7 to 65.2 %, while the contents of clay and colloidal particles varied from 29.2 to 49.7 % (Fig. 6). For the palaeosol layers, the silt particles varied from 43.5 to 59.8 % while the clay and colloidal particles varied from 37.3 to 56.2 % (Fig. 6). The percentage of silt particles in the loess layers was higher than in the palaeosols and, conversely, the contents of clay and colloidal particles in the loess were lower than in the palaeosols. By comparing the curves of porosity and grain size with depth (Figs. 5 and 6), one finds that the layers with higher porosity have higher silt and lower clay contents: this implies that the porosity of the loess and palaeosol layers mainly varies with the relative amounts of clay and silt. In other words, the finer the grain size, the lower is the porosity.

Zhao et al. (2002) investigated the water-bearing capacity of loess and found that the higher porosity is a necessary condition for forming water-bearing spaces. Our measurements show that the grain size of loess is coarser than the palaeosols, and the porosity of loess is greater than the palaeosols. Therefore, this means that the water-bearing space of the loess is better developed than the palaeosols.

Aquifers and aquitards and the loess-palaeosol layers

There are two necessary conditions for the formation of an aquifer: (1) adequate permeability of the sediments and (2) sufficient water-bearing space. In the samples from the studied Shuangzhu section, the permeability of the loess layers was greater than the palaeosol, and the water-bearing space of the loess was more developed compared with the palaeosol. Therefore, in this loess-palaeosol layer, the loess layers are likely to form the aquifers and the palaeosol layers form relatively aquitards.

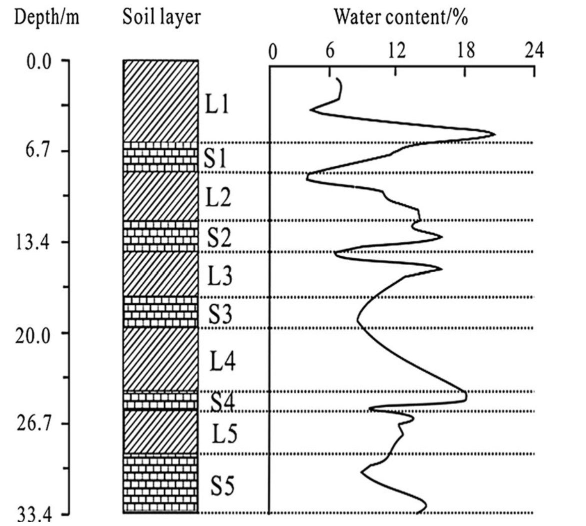

Fig. 7 Water content of soil layers from *L1* to *S5* at Shuangzhu in Chang'an

The water content measurement for the present study shows that the water content of the loess layers ranged from 7.9 to 21.4 %, while the palaeosols ranged from 4.1 to 21.4 % (Fig. 7). The average water content of the loess layers (34 %) is substantially higher than the palaeosol (7 %). Those layers with the highest water content usually appear in the lower parts of loess and seeping water is often evident above the palaeosol layers. Field studies of loess from the Yangwan section, which is about 6 km to the south of the Shuangzhu section, showed multilayer groundwater outflows from the loess layers; this was attributed to the low-lying terrain (Zhao et al. 2002). These suggest that the loess layers can form aquifers and the palaeosol layers are more prone to form aquitards.

However, this is not always the case. For example, S4 developed in humid conditions, and it has a relatively large infiltration rate owing to the numerous longitudinal fissures in the layer which is also only 1.4 m thick. As a result, S4 does not function as an aquitard. In addition, palaeosol layers can occasionally act as aquifers because the bottoms of these layers typically have lower porosity than the upper portions.

Climate and hydrological systems

Previous studies have shown that the carbonate content and magnetic susceptibility in loess can reflect climatic and environmental change (Liu 1985; Zhao et al. 2008). Generally, the higher carbonate content and lower magnetic susceptibility indicated the colder/drier climatic conditions when loess was deposited and, conversely, the lower carbonate content and higher magnetic susceptibility indicated the warmer/wetter climatic conditions. The information on

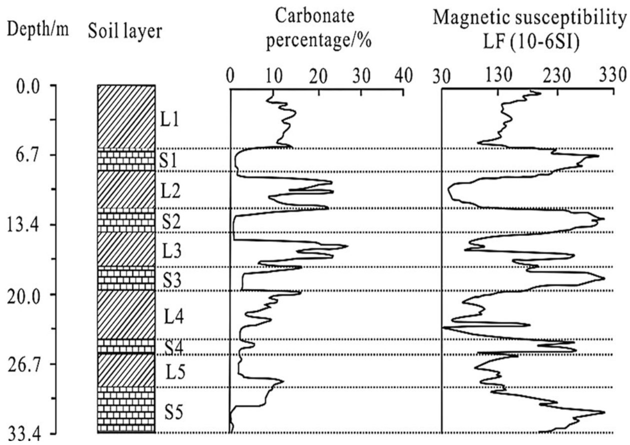

Fig. 8 Carbonate mass percentage and magnetic susceptibility of soil layers from *L1* to *S5* at Shuangzhu in Chang'an

the carbonate contents of the soil and magnetic susceptibility also can provide an important means for understanding the pedogenesis of the loess layers and palaeosols (Deng et al. 2007; Xu et al. 2000; Zhu et al. 1995). Along these lines, the carbonate content and magnetic susceptibility in this loess-palaeosol section were studied. The average carbonate mass percentages in the loess layers ranged from 7.01 to 15.18 %, while the palaeosols' average carbonate mass percentages ranged from 0.46 to 1.28 % (Fig. 8). The low-frequency magnetic susceptibility in the loess layers varied from 35 to 311.7 (10^{-6} SI) and for the palaeosols from 9 to 326 (10^{-6} SI) (Fig. 8). These results tell a consistent story. That is, the palaeosol layers developed in warmer/wetter climatic conditions, and these sediments were subject to stronger pedogenesis than the loess which was deposited during colder/drier times.

Pedogenesis under warmer/wetter climatic conditions was stronger than under colder/drier climatic conditions when loess was deposited and, as a result, sediments in the loess layers are coarser than those in the palaeosol. Grain size also can reflect the degree of pedogenesis, and this property of the soils is connected to the climate conditions at the time the sediments were deposited (Lu and An 1998; Sun and Lu 2007). In the context of this discussion, the stronger pedogenesis led to finer grain size and lower porosity. Compared with the palaeosol layers, the porosity of the loess is greater, the permeability of the loess is greater, the water content of loess is higher, and the water-bearing space of the loess layers is better developed. The net result of these effects is that the loess layers can form aquifers while the palaeosol layers are more prone to form aquitards. While other factors also influence the water-physical properties of loess and palaeosol, including the depth of the strata, their thicknesses and so on, these factors evidently are less important than palaeoclimate. So the grain size and porosity of the loess-palaeosol sequence are mainly controlled by climate conditions at the time of deposition, and these factors determine the development of permeability and water-bearing spaces.

Above all, the present study shows that the climate during the Pleistocene yet controls the modern hydrological properties of sediments from the southern Chinese Loess Plateau. Further, Quaternary climatic change has largely determined whether aquifers and aquitards occur in the contemporary loess and palaeosol.

Conclusions

The Quaternary climatic change is the dominant factor for forming aquifers and aquitards in the loess and palaeosol layers. The pedogenesis under the warmer/wetter climatic conditions is stronger than under the colder/drier climatic conditions, and then it influences the water-physical property of loess and palaeosol layers. Under the pedogenesis influence, the grain size of loess layer is coarser than the palaeosol layers, the porosity of loess layers is higher than the palaeosol layers, the permeability of the loess is stronger than the palaeosols, the water content of the loess layer is higher than the palaeosol layers, and the water-bearing space of the loess layers is better developed than the palaeosol layers. By contrast, the loess layers can form aquifers and the palaeosol layers are more prone to form aquitards. In short, the Pleistocene climate change has an important controlling action on modern hydrological systems in the southern Chinese Loess Plateau.

This study then demonstrates how knowledge of the interactions between palaeoclimate and the geological properties of loess-palaeosol sequences can be used and applied to modern hydrological systems. Indeed, there are important implications of these findings, not only in terms of water resources but also with respect to the suitability of the sedimentary sites for building construction. This is because the geophysical characteristics of the sedimentary layers are directly related to their ability to withstand floods and other catastrophic events such as earthquakes. Moreover, additional research on climate, loess, and hydrology will likely lead to other important environmental insights.

Acknowledgments This work was supported by the National Natural Science Foundation (40672108 and 41210002), Fundamental Research Funds for the Central Universities (GK201302033), and the State Key Laboratory of Loess and Quaternary Geology, Chinese Academy of Science (SKLLQG1214).

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