Research Paper

Effects of pore water chemistry on hydraulic conductivity of saturated loess

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ARTICLE INFORMATION

ABSTRACT

The effects of pore water chemistry on hydraulic conductivity of saturated loess are investigated. A series of laboratory tests were conducted to investigate these effects with different salt concentrations, cations, and anions. The results showed that with increased NaCl concentration, the hydraulic conductivity of the loess samples decreased below 14%, but an increase occurred at 16%. The hydraulic conductivity of loess samples with different cations in the permeant decreased in the following order: $Ca^{2+} > K^+ > Na^+$, which was mainly affected by the different valence and hydrated ion radius thereof. The effects of different anions on loess permeability were influenced by their ability to influence the activity of cations, and the hydraulic conductivities were in order: $Cl^- > SO_4^{2-} > HCO_3^-$. To investigate the major mechanisms involved in variations in hydraulic conductivity, the trends in sample hydraulic conductivity and intrinsic permeability to different salt solutions were compared. The similar plots revealed that the changes in hydraulic conductivity were attributed to changes in soil fabric, which was due to the change of electric double layer thickness and charge characteristics of certain soil mineral surfaces and edges, rather than the density and viscosity of those permeating fluids. In addition, the implications for water-induced hazards were also discussed.

1. Introduction

Seepage problems are related to the hydraulic characteristics of a soil mass, such as the transport of chemicals, distribution of water resource, and the mechanical performance. In general, as an important issue affecting seepage problems, permeability is mainly affected by soil fabric, *e.g.* pore size, particle size, shape, and arrangement (Ozgurel and Vipulanandan, 2005; Shepherd, 1989). Soil structure is also influenced by the permeating fluids, especially for salt solutions. The variation of hydraulic conductivity of a soil can be considered as a comprehensive result of the interaction of water, chemicals, and soil particles.

It has been reported that the influence of salt solutions on soil hydraulic conductivity mainly depends on salt concentration, chemical composition and ion type (Levy *et al.*, 2005; Madsen and Mitchell, 1989; Pupisky and Shainberg, 1979). Tests on clayey soils have shown that the concentration decrease always results in a reduction in hydraulic conductivity within a specific range of salt solution concentrations (Mishra *et al.*, 2009; Russo and Bresler, 1977; McNeal and Coleman, 1966). Hydraulic conductivity variations resulting from salt

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composition were investigated in many different ways, such as employing different ions in one test and changing the quantity thereof, or replacing a specific ion and so on. For example, soil permeability relating to the quantity of Ca^{2+}, K^+, Na^+, and Mg^{2+}, such as sodium adsorption ratio (SAR) and potassium adsorption ratio (PAR), were published (Arienzo *et al*., 2012; Mace and Amrhein, 2001; Chen *et al*., 1983), but the results were different or even contradictory. The effects of cations on soil hydraulic conductivity were also observed in many projects (Shariatmadari *et al*., 2011; Jo *et al*., 2005; Kolstad *et al*., 2004), which show that divalent and trivalent cations produce a higher permeability than monovalent cations. While the performance of anions as they affect hydraulic properties were less often reported, most existing observations indicate that some anions can be absorbed on the edge surface of specific minerals, which will change the surface charge and reduce the attractive force between soil particles, and then reduce the number and size of flow channels (Frenkel *et al*., 1992; Shanmuganathan and Oades, 1983). Collectively, these studies indicate that salt solutions have a pronounced influence on soil fabric, which controls the hydraulic conductivity.

Typically, most of the current studies were conducted on the potential civil engineering applications of the materials which were made up with clayey soils, such as ponds, canals, and reservoirs *etc*. There are few investigations reported on the effects of inorganic salt solutions on loess permeability. The objective of this work is to explore the effect of different cations, anions, and salt concentrations on the hydraulic conductivity and microstructure of loess. The results of this study may have significant implications for the understanding of the relationship between chemical characteristics and water-induced hazards occurring in irrigated loess areas, such as landslides, subsidence, and debris flow.

2. Materials and methodology

2.1 Soil and test samples

The samples were prepared with loess collected from Lanzhou City, Gansu Province, China. The soil is comprised of 92% silt, 7% clay, and 1% sand (Table 1). Fig. 1 shows the grain size distribution curve.

The microstructure of the undisturbed and remoulded loess samples were observed using SEM analysis (Fig. 2). As shown in Fig. 2, both samples consist of a loosely-packed silt skeleton with finer particles coating larger particles forming aggregates, and the aggregates formed bigger clusters which appeared more irregular in shape in undisturbed loess, while those in the remoulded loess formed a more extensive homogenous structure.

Table 1. Basic physical properties of loess

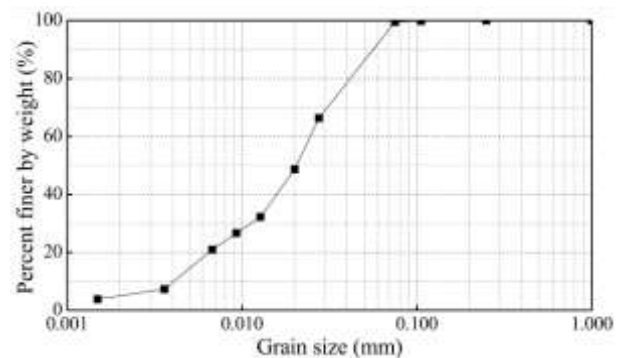| Properties	Value
Specific gravity	2.71
Initial moist bulk density (g/cm³)	1.50
Liquid limit (%)	27.76
Plastic limit (%)	17.68
Plasticity index (%)	10.06
Mean size (mm)	0.018
Uniformity coefficient	5.50
Organic matters content (%)	0.87
Electrical conductivity (ms/cm)	0.65
Total dissolved solids (ppm)	460

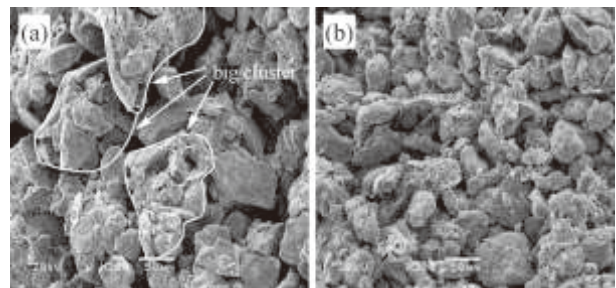**Fig. 1.** Grain size distribution of loess

Fig. 2. Microstructures of the loess samples, (a) undisturbed (b) remolded

The mineral composition of the raw loess samples was determined using the X-ray powder diffraction (XRD) analyzer (a Philips PW 3710 diffractometer at a rate of 0.05°/s) (see Fig. 3), showing that the loess samples are mainly composed of quartz, calcite, and clay minerals.
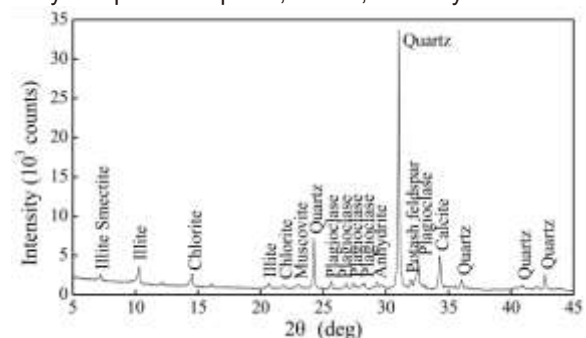

Fig. 3. X-ray diffraction pattern of the loess

2.2 Preparation of permeating solutions

According to the quality analysis of spring water drained from Heifangtai terrace (Table 2) (Yan, 2015), a typical loess area in which water-induced landslides occurred was sampled and Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^- were assayed.

To test the effects of salt concentration on hydraulic conductivity of the loess samples, analytical pure sodium chloride (NaCl) was dissolved in de-aired distilled water to the desired concentrations (i.e., 3%, 6%, 10%, 12%, 14%, and 16% by weight), and the de-aired distilled water was deemed to be equivalent to 0%. To test the

effects of different cations on the loess permeability, Na^+, K^+, and Ca^{2+} were used in the permeant solutions, which were made from analytical pure NaCl, KCl, and $CaCl_2$ respectively. Cl^-, SO_4^{2-}, and HCO_3^- were used to test the effects of anions on the loess permeability, and the solutions were made from analytical pure NaCl, Na_2SO_4 and $NaHCO_3$, respectively. Each ion to be tested was dissolved in de-aired distilled water to the same concentration (1 mol/L). During the preparation of the permeant fluids, all salts were fully dissolved and then sealed in a container, separately. The solutions should not precipitate or be contaminated.

Table 2. Chemical constituents of the spring water drained from Heifangtai terrace

Sample number	pH	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1	7.20	33366.0	2758.9	9645.6	23138.5	358.4	1303.6	1968.9	60.0
2	--	42173.1	3547.7	9605.0	27508.2	454.5	1529.0	1877.0	42.3
3	7.00	33313.2	2410.5	7529.0	18963.5	78.1	1127.5	1356.6	21.7
4	7.43	20811.7	1446.0	11897.1	15792.5	137.9	848.0	1134.6	32.2
5	7.66	7064.8	535.3	11082.9	8348.3	49.6	439.6	747.1	32.4
6	7.55	6829.6	506.8	8827.9	6503.7	40.2	345.3	589.0	57.6
7	7.41	12936.0	1034.7	11557.6	12243.0	101.3	769.3	1183.4	74.6
8	7.34	15396.8	1103.7	10101.4	11845.8	66.2	657.9	897.4	30.9
9	7.67	30358.0	2346.8	9300.6	20215.8	83.7	1200.8	1525.7	68.6
10	7.42	28336.0	2253.7	9890.5	19604.6	128.5	1216.4	1603.7	66.5
11	7.44	23850.8	1682.3	10992.0	15392.3	69.0	848.5	1035.4	29.7
12	7.35	19135.0	1404.7	10248.0	14324.4	59.6	764.7	1036.0	27.6

2.3 Preparation of permeation samples

Before the preparation of permeation samples, the undisturbed loess was air-dried, powdered by a plastic hammer and sieved to obtain a sample graded to 1 mm diameter grains. The permeation samples were prepared with the same initial dry density (1.5 g/cm³) and water content (17.64%), which was in accordance with the maximum dry density and optimum water content of this loess sample. During the preparation of remoulded samples for permeability testing, distilled water was first sprinkled on the air-dried and powered loess to reach different desired water contents. To ensure a homogeneous sample, the wetted loess was mixed and ground by hand, and passed through a 1 mm aperture sieve. The reason for selecting the size of sieve was that the grain size of this loess was less than 1 mm. To achieve the desired water content, appropriately more water was added to the samples because of a certain amount of loss during grinding and sieving. Thereafter, the samples were sealed using an opaque plastic film and stored for 24 hours in an air-conditioned room to allow equilibration of the moisture distribution therein. Then, the desired amount of each bulk sample was calculated based on the desired water content (17.64%), dry density (1.5 g/cm³) and volume of mould (7 cm × 7

cm × 7 cm) before being placed into a forming mould. Then the samples were statically compacted with the help of a press machine under a constant pressure. All bulk samples were cut with chamfered cutting rings of 6.18 cm inner diameter and 4 cm height. It is necessary to paste the inner rigid wall of each cutting ring with a thin layer of Vaseline to prevent side-leakage between the interface of the cutting ring and soil sample: the ring sample was cut so as to minimize sample disturbance. Even slight disturbance may significantly increase the permeability of the sample; because the permeant fluids are almost all salt solutions, saturation before permeability testing can alter the soil fabric and obliterate the trend in hydraulic conductivity over time. The sample with distilled water as a permeant was vacuum-saturated before permeability testing, and the other samples tested with salt solutions were saturated during the initial stage of permeability testing. Therefore, the permeation process of soil samples (except in the case of distilled water as the permeant) also included a saturation stage.

2.4 Permeability test

Permeability testing was performed to measure saturated hydraulic conductivity according to Chinese Standard Procedures (GB/T50123, 1999, falling-head

method). Each of the prepared samples was permeated using a rigid wall permeameter. During each permeability test, the samples were enclosed by the permeameter with free pressure in any dimension and isolated from the atmosphere. Hydraulic conductivities of the samples were calculated using Darcy's law:

$$k = 2.3 \frac{aL}{At} \log \frac{h_1}{h_2} \qquad [1]$$

where k is the hydraulic conductivity, a is the inner cross-sectional area of the standpipe, L is the height of the soil sample column, t is the recorded time for the water column to flow though the sample, h_1 is the initial water level in the standpipe and h_2 is the lower water level after time t. To minimize error in manual recording, h_1 and h_2 were kept equal in each test so that the hydraulic gradients were constant. An individual permeability test was terminated when two criteria were satisfied: no further change in hydraulic conductivity was observed, and the other was that the solution concentration in the effluent liquid was approximately equal to that in the influent liquid. The saturated hydraulic conductivity of an individual test was obtained by averaging the hydraulic conductivity values in the final equilibrated stage. A typical permeability test was replicated three times and each test took about one or two days to reach equilibrium. The final hydraulic conductivity of each sample (as presented in Figs 4(b), 5(b), and 6(b)) was the average value of three replications.

3.   Results

3.1 Effects of salt concentration

Fig. 4b shows that with the increase in NaCl concentration, in the range of 0% to 14%, the hydraulic conductivity decreases from 2.99×10^{-4} to 8.12×10^{-5} cm/s, and increases to 1.22×10^{-4} cm/s at 16%. It can be seen that the hydraulic conductivities of samples with salt solutions as permeant are much smaller than that using distilled water. This may be attributed to two factors: the lower flow velocity of salt solutions resulting from the higher viscosity and density, and that, during a permeability test, clay particles were deflocculated by the NaCl solution and consequently caused smaller flow channels compared to those in the original sample. The changes in loess permeability with increasing salt concentration differed from the permeability test results obtained from clayey soils, in which the permeability directly increased with salt concentration (Paes *et al*., 2014; Madsen and Mitchell, 1989).
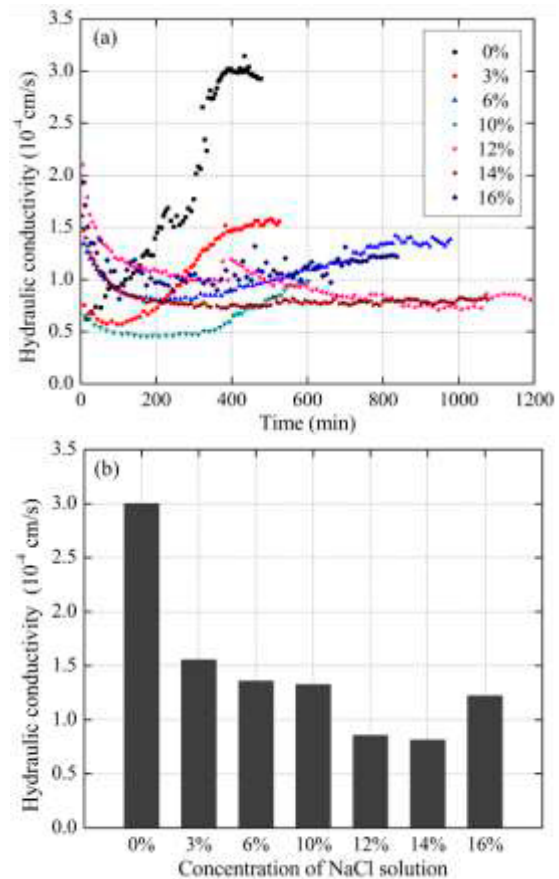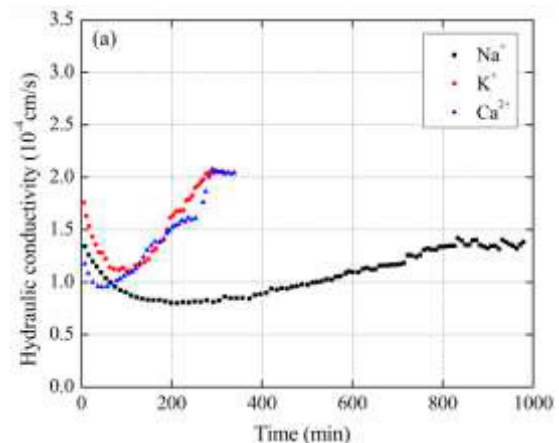

Fig. 4. (a) Change in hydraulic conductivity with permeating time under different NaCl concentrations; (b) Hydraulic conductivities in dependence on various NaCl concentrations.

3.2 Effects of ion type

The hydraulic conductivities of samples permeated with different cations are shown in Fig. 5b. There is little difference between the hydraulic conductivities of samples with Ca^{2+} and K^+ as the fluid permeant (2.05×10^{-4} cm/s and 2.04×10^{-4} cm/s correspondingly), which are much greater than that with Na^+ (1.36×10^{-4} cm/s). The result indicates that the influence of Ca^{2+} and K^+ on loess hydraulic conductivity was significantly different from that of Na^+ even at the same concentration.
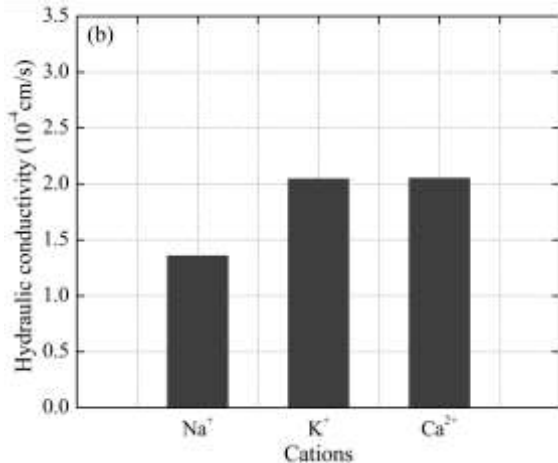
Fig. 5. (a) Change in hydraulic conductivity with permeating time based on different cations; (b) Hydraulic conductivities in dependence on various cations.

Fig. 6b shows the response of loess sample permeability to different anions. The hydraulic conductivity of samples with Cl^- in the permeant (1.36 × 10^{-4} cm/s) was greater than those using SO_4^{2-} and HCO_3^- in the permeant (8.77 × 10^{-5} cm/s and 4.81 × 10^{-5} cm/s correspondingly), and the minimum value was obtained with HCO_3^-, which also had the lowest value among all of the hydraulic conductivities tested.
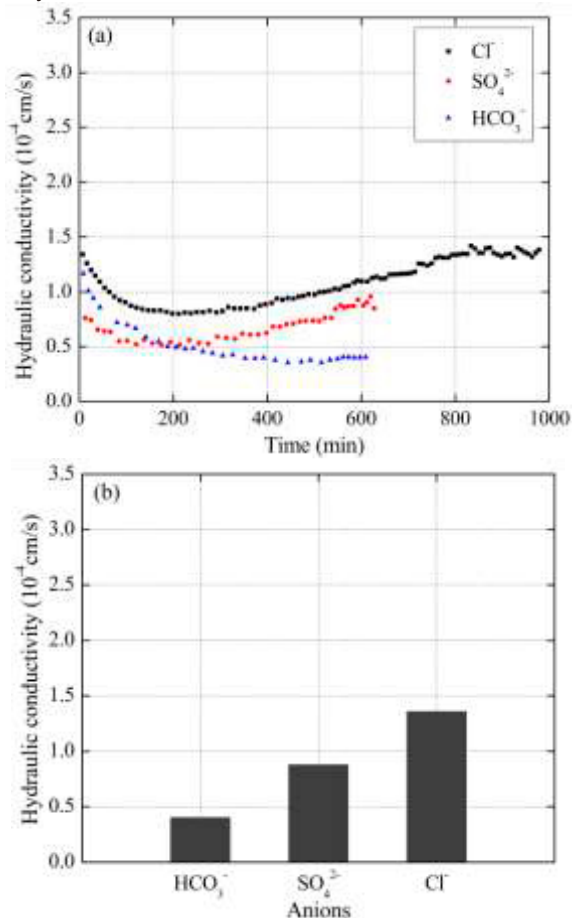

Fig. 6. (a) Change in hydraulic conductivity with permeating time based on different anions; (b) Hydraulic conductivities in dependence on the various anions.

3.3 Changes in hydraulic conductivity with permeating time

Changes in hydraulic conductivity with permeating time were also observed (Figs 4a, 5a, and 6a). In the initial stage of each permeability test, each sample (except that with distilled water as the permeant, which was vacuum saturated before permeability testing) exhibited a higher hydraulic conductivity, while this later decreased and finally increased to different extents. The reduction in hydraulic conductivity was due to the saturating process applied in the initial stage of the permeability testing, during which the liquids flowed into soil pore accompanied by clogging with air bubbles and fine particles. With the constant inflow of the permeant solution, air bubbles and fine particles were cleared, and the hydraulic conductivity reduced at a lower rate with time. Until the samples were saturated and the flow channels were completely unblocked by the seepage force, the decrease ceased and the hydraulic conductivity then remained relatively stable for a period of time. When final equilibrium was reached, the soil particles had interacted with permeant fluids in the former stages and gradually formed large aggregations which caused the increase in hydraulic conductivity.

Besides, the permeability increase in samples with a distilled water permeant can be explained as follows: small amounts of micro-particles can be transported by the effluent water, and some solute salts or minerals in the loess samples can be dissolved by the distilled water. When steady flow channels formed, the hydraulic conductivity would not increase: that is also the second most important factor causing the permeability increase in samples permeated by salt solutions besides the interaction between salts and clay particles.

4. Discussion

4.1 Chemical effects of different NaCl concentrations on loess permeability

As has been established, the NaCl concentration always increases the permeability of clayey soils, which is quite different from the results observed here (Montoro and Francisca, 2010; Jo et al., 2005). The clayey soil is more sensitive to salt than the loess, thus with increases in NaCl concentration, the repulsive force between clay particles decreases with the reduction of electric double layer thickness between the soil particle surface and pore fluid, and the clay particles were flocculated by the van der Waals forces (Mitchell, 1991; Barbour and Fredlund, 1989); because the size and distance between the

particles are very small in clayey soils, this results in small voids and poor permeability and once the aggregations formed, the hydraulic conductivity will increase immediately. While in loess samples, the clay content is much lower than in clayey soils, and more importantly, the fabric and function of clay particles are quite different from those of clayey soils. In particular, silt grains are assembled with clay particles which play a major role in bonding the loess skeleton. When the NaCl concentration increased from 0% to 14%, clay particles tend to be attracted more strongly and bound to the silt grains more tightly, which reduced the pore volume between the silt grains and caused the decrease in hydraulic conductivity; but during the flocculation of clay particles between the silt grains, bigger aggregations (coarser than clay particles) also formed and resulted in larger pore volumes. So when the NaCl concentration increased (to a certain extent) that caused the aggregations to be dominant features in the loess fabric, the flow channels expanded, and then the hydraulic conductivity increased.
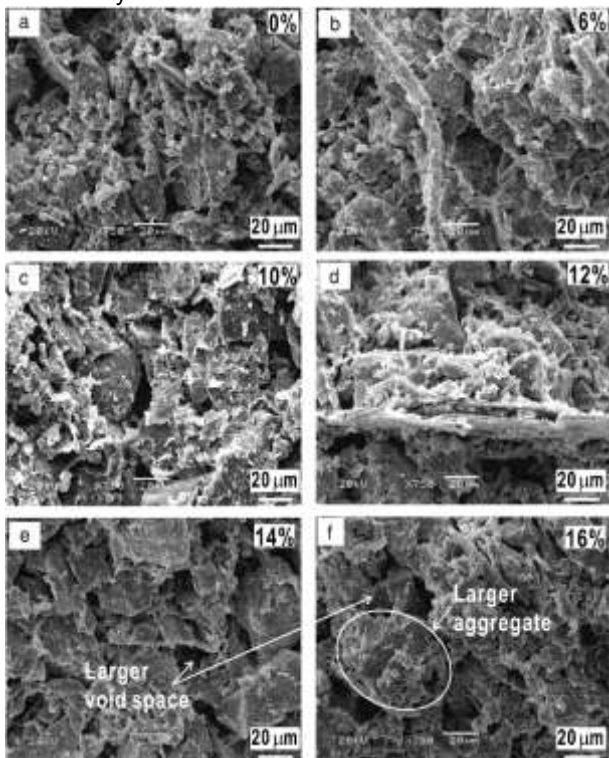

Fig. 7. SEM images of the samples collected from Heifangtai terrace saturated by different NaCl concentrations. (a) 0%; (b) 6%, (c) 10%; (d) 12%; (e) 14%; and (f) 16%. (Zhang et al., 2013)

The microstructure changed with NaCl concentration (Fig. 7) (Zhang *et al*., 2013), as observed in the loess samples from Heifangtai terrace. The SEM images show that the clay particles gradually aggregated with increasing NaCl concentration (when below 12%). During this process, the silt grains became more closely packed and the pore space therein was minimized, however, above concentrations of 12%, additional NaCl resulted in

the formation of aggregation clusters and thus formed larger void spaces. As seen in Figs 7e and 7f, the loess fabric was dominated by these clusters and larger void spaces which could lead to the increase in hydraulic conductivity. Thus the change in hydraulic conductivity at different NaCl concentrations can be explained by the principle observed in Fig. 7. Little difference was found between the "critical concentrations" (12% and 14%), under which the larger pore voids formed. This phenomenon may be due to the fact that the loess sample obtained from Heifangtai terrace contains more soluble salts than that in this study.

On the other hand, Cl$^-$ can act to diminish the positive effect of Na$^+$ on flocculation, and the negative effects of Cl$^-$ decrease with its concentration (Nguyen *et al*., 2013). In this observation, when a relatively low concentration of NaCl was used, the effect of Na$^+$ was partly masked by Cl$^-$, and mitigated the formation of aggregations of grains, thus the hydraulic conductivity decreased with increasing NaCl concentration (when below 12%); however, with increasing NaCl concentration, Na$^+$ and Cl$^-$ both reached high concentrations so that the diminishing Cl$^-$ content decreased to a very low level. Meanwhile, the positive effect facilitating flocculation of Na$^+$ increased and accelerated the formation of aggregations. As a result, the aggregations became dominant in the loess fabric and finally caused the increase in its permeability at 16% concentration.

Hydraulic conductivity variations with different permeant cations are attributed to the compression of the electronic double layer. As the most important factor among those that influence the repulsive force, the thickness of the electronic double layer is controlled by the valence and hydrated ion radius of cations, and this even exceeds the effects of surface charge density, thermal agitation, and ionic concentration (Montoro and Francisca, 2010; Madsen and Mitchell, 1989). It has been demonstrated that, with the increase in valence and decrease in hydrated ionic radius, the electronic double layer thickness can be reduced and the attractive force among soil particles increases (Rao and Mathew, 1995), which promotes particle growth and creates a more significantly flocculated fabric (Mitchell and Soga, 2005; Madsen and Mitchell, 1989). Since Ca^{2+} is of a higher valence than Na$^+$ and K$^+$, Ca^{2+} has the greatest ability to compress the thickness of the electronic double layer among the cations used in this investigation. It means that the sample with Ca^{2+} in the permeant was most likely to form aggregations, which could lead to large pore space allowing its flow. For the monovalent cations, Na$^+$ and K$^+$, the hydrated ionic radius of Na$^+$ (0.45 nm) is greater than that of K$^+$ (0.3 nm) (Jo *et al*., 2001; Burgess, 1999). Therefore, the ability of a cation to generate a

more flocculated soil fabric, in order, was: Ca^{2+} > K^+ > Na^+, and as a consequence, the hydraulic conductivity to permeants containing of Na^+, K^+, and Ca^{2+} increased in sequence (Fig. 5b).

Generally, the influence of anions on soil fabric is due to the change in the charge characteristics of soil particles, which is affected by the pH value in the solution system and the effects of anions on cation activity (El-Swaify, 1973). When the soil particles were exposed to a pore solution containing a lot of anions, some of the anions were absorbed by certain minerals. The surface positive charges were partly neutralized, which induced the increase in repulsive force between soil particles and was conducive to formation of a less flocculated state (Lourenço et al., 2006; Chorom and Rengasamy, 1995). Since the affinity of Cl^- is lower than those of SO_4^{2-} and SO_4^{2-}, it requires more capacity for neutralizing positive charges than Cl^- (Nguyen et al., 2013), SO_4^{2-} is more effective in facilitating dispersion than Cl^-, and consequently generated a lower permeability; besides, the pH increased in the pore solution, which is more pronounced than the effects of anion adsorption with regard to deflocculation or dispersion (El-Swaify, 1973), and can produce a higher negative surface charge on the clay particles and a larger double layer thickness. Hence a higher pH value will increase electrostatic repulsion and the clay particles will be less flocculated (Palomino and Santamarina, 2005; Greberg and Kjellander, 1998). Hydrolysis of HCO_3^- meant that a $NaHCO_3$ solution had a higher pH than Na_2SO_4 and NaCl (Table. 3), and herein, this caused a less flocculated structure than Cl^- and SO_4^{2-}, therefore the hydraulic conductivities decreased in the following order: Cl^- > SO_4^{2-} > HCO_3^-.

Table 3. The pH value and hydraulic conductivity of samples permeated with different anions.

Anions	Hydraulic conductivity	pH
Cl^-	1.36×10^{-4} cm/s	7
SO_4^{2-}	8.77×10^{-5} cm/s	7.3
HCO_3^-	4.81×10^{-5} cm/s	8.3

To verify that the hydraulic conductivity variation was caused by the change in loess fabric rather than the intrinsic dynamic properties (i.e., viscosity and density) of the permeating solutions (Table 4), the intrinsic permeability of each solution was calculated as follows (Fernandez and Quigley, 1988):

$$K = \frac{k\mu}{\gamma} = \frac{k\mu}{\rho g} \qquad [2]$$

where K is the intrinsic permeability (cm^2); k is the hydraulic conductivity (cm/s); μ is the dynamic viscosity of the permeating fluid (g/(cm·s)); γ is the unit weight of the permeating fluid (g/(cm/s^2)); ρ is the density of the permeating fluid (g/cm^3); g is the acceleration due to gravity (980 cm/s^2). As shown in Figs 8a to 8c, the

changes in intrinsic permeability with different concentrations and ions were similar to those of hydraulic conductivity of the loess samples. The results indicate that the difference in hydraulic conductivity was mainly caused by the pore volume and particle arrangement (Jo et al., 2001). The results also revealed that the chemical effects are more predominant than viscosity and density in influencing the hydraulic conductivity.
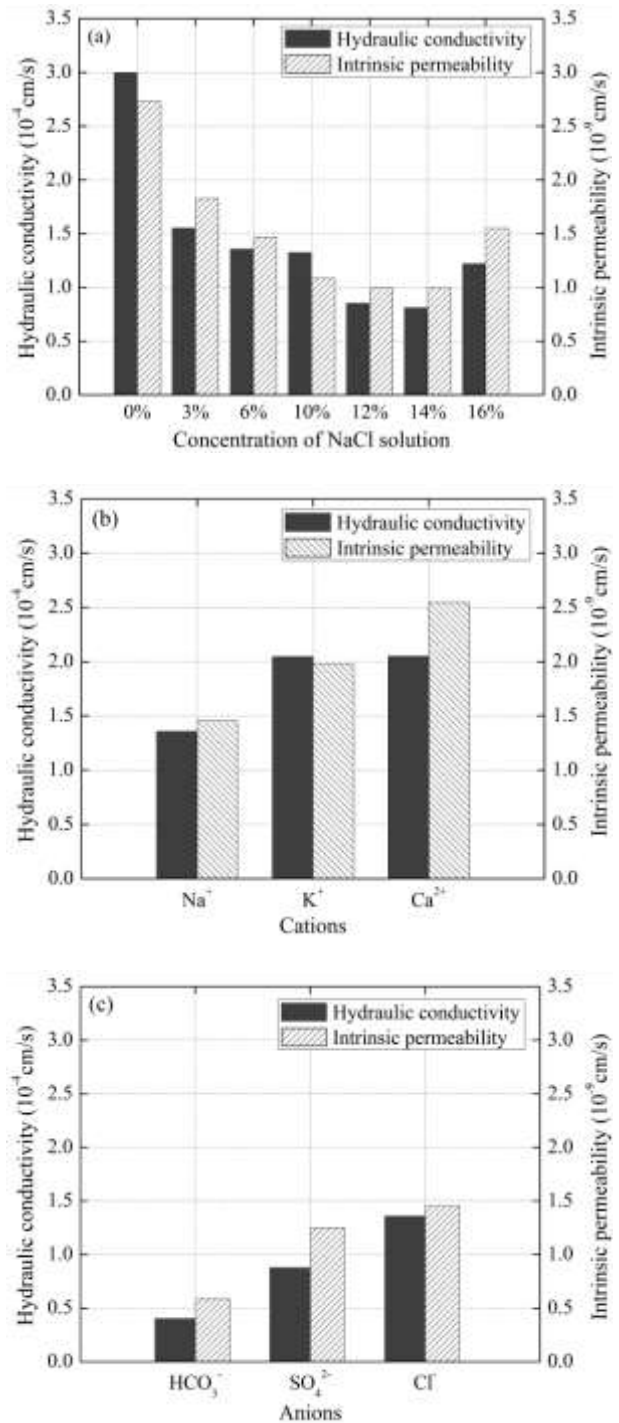

Fig. 8. (a) Hydraulic conductivity and intrinsic permeability as a function of NaCl concentration; (b) Hydraulic conductivity and intrinsic permeality based on different cations; (c) Hydraulic conductivity and intrinsic permeability based on different anions.

Table 4. Viscosity and density of permeating fluids

	Solution	Concentration	Viscosity g/(cm·s)	Density g/cm³
Different concentrations	Distilled water	0%	0.894	1.000
	NaCl	3%	1.052	1.020
	NaCl	6%	1.104	1.041
	NaCl	10%	1.193	1.071
	NaCl	12%	1.250	1.086
	NaCl	14%	1.317	1.101
	NaCl	16%	1.388	1.116
Different cations	NaCl	1mol/L	1.093	1.041
	KCl	1mol/L	0.991	1.044
	CaCl$_2$	1mol/L	1.326	1.089
Different anions	NaCl	1mol/L	1.093	1.041
	Na$_2$SO$_4$	1mol/L	1.562	1.117
	NaHCO$_3$	1mol/L	1.258	1.055

4.2 Implication for water-induced geologic hazards

Many water-induced geological hazards or environmental problems, regularly occurring in loess areas, are influenced by hydrological factors: permeability variations can be identified as a key factor in controlling the occurrence of geological hazards, such as landslides, subsidence, and debris flows.

In the case of Heifangtai terrace, long-term excessive irrigation has caused large-scale subsidence and landslides. The influx of water has elevated the groundwater table, and reduced the effective stress in the soil: the influx of water has also dissolved salts in the soil mass or diluted the pore solution resulting in a decrease in salt concentration. The desalinization increased the hydraulic conductivity and reduced both the peak and steady-state shear strengths (Zhang *et al*., 2013). As a consequence, a higher hydraulic conductivity facilitated more water infiltration into the soil mass, and accelerated the mechanical erosion thereof.

Excessive pore water pressure has also been considered as an important factor driving slope failure (Ochiai *et al*., 2004; Bonte *et al*., 2000; Harp *et al*., 1990). A series of test results have revealed that the increase in pore pressure has an adverse effect on soil strength (Wang *et al*., 2007; Lourenço *et al*., 2006). In natural slopes, the high pore water pressure is generally developed within layers of high permeability surrounded by low-permeability materials, which act as a physical barrier to groundwater flow (Lourenço *et al*., 2006). The excessive pore water pressure causes a significant reduction in shear strength, while its dissipation reduces the risk of slope failure. Among the factors influencing pore water pressure, soil permeability is critical in arid and semi-arid regions, various scales and extents of evaporation, rainfall and infiltration cause variations in

groundwater distribution and composition, and consequently create a wide range of geological hazards. Moreover, in some salt-abundant areas, salts may accumulate in surface soils by evaporation of saline surface water from poorly drained areas, and cause great damage to agriculture (Peck, 1978).

4.3 Study limitation

In this study, the relationships between water chemistry, the dynamic properties of the permeating fluids, soil fabric, and the occurrence of water-induced geological hazards were discussed on the basis of obtained from the permeability testing of loess samples at various NaCl concentrations, and in the presence of other cations and anions; however, there following limitations remain:

(1) In the permeability tests, the criterion of achieving chemical equilibrium was only a concentration equivalence of outflow and inflow while EC and pH were not measured;

(2) Being restricted by the test equipment, the flow volume was not measured;

(3) Weathering of samples changed the void ratios and this was not measured. How to maintain the integrity of the sample structure during air-drying will be explored in further research.

5. Conclusions

The effects of different solution concentrations, cations, and anions on the hydraulic conductivities of loess have been investigated.

(1) The hydraulic conductivity of the loess decreased as the NaCl concentration of the permeating fluid increased (below 14%) while it increased afterwards due to the flocculation of clay particles which developed bonds between silt grains, and because of the interaction between Na$^+$ and Cl$^-$.

(2) The effects of cations on the hydraulic conductivity of loess depended on the ability of cations to compress the electronic double layer. A higher valence and smaller hydrated ionic radius led to a thinner electronic double layer and generated a more flocculated fabric, all of which produced a higher hydraulic conductivity.

(3) Results obtained from the anion group arose because of the change in the charge characteristics of the soil particles, as influenced by fluid pH and the capacity of those anions to neutralize positive charges: the pH effect was more predominant than that of anion adsorption. In fact, the permeability of loess samples with anions was significantly influenced by the activities of cations absorbed on surface of the soil particles.

(4) The results of permeability testing indicated that the variation in loess permeability was mainly caused by the change in pore volume and particle arrangement resulting from chemical effects, rather than from the intrinsic dynamic properties of the permeating fluids. Furthermore, loess permeability was closely related to the occurrence of geological hazards from the perspective of soil strength reduction, as caused by: salt dissolution, mechanical erosion, and excessive pore water pressures.

(5) There are some limitations to this study, including: the criterion used to determine chemical equilibrium, pore space flow and volume changes with permeating time and void ratios before, and after, permeability tests, all of which were not controlled here. These limitations were mainly a facet of the test conditions and will be explored in future work.

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