Study on the mechanism of loess landslide induced by chlorine salt in Heifangtai terran

Juan Wang i,ii), Wei Liu i,ii), Wenwu Chen i,ii), Peng Liu i,ii), Bobo Jia i,ii), He Xu i,ii), Li Wen iii)

i) Department of Geological Engineering, Lanzhou University, Tianshui Road, 222, Lanzhou 730000, China
ii) Key Laboratory of Mechanics on Disaster and Environment in Western China, Ministry of Education, China
iii) School of Information Science and Technology, Lanzhou University, Lanzhou 730000, China

ABSTRACT

It is well known that water content is the key factor affecting the loess strength. In arid and semi-arid regions, the salt content in pore solution of loess is relatively high. Rainfall or irrigation can change the water content of loess and induce geological disasters such as loess landslide and loess mud flow. In this paper, Heifangtai, Gansu Province, is chosen as the study site, where is the most typical place of loess landslides. The occurrence of loess landslides is closely related to water, salt. In order to investigate the interaction rules of these three factors, a series of pressure plate apparatus tests and undrained shear tests were conducted on saturated loess, to investigate the degradation mechanism of loess strength caused by the interaction between water and salt. The results showed that NaCl concentration had a significant effect on the matrix suction, i.e. the water retention capacity of loess sample increased as the increase of NaCl concentration, especially in the boundary effect zone (low suction zone, soil almost saturated), concerning the remolded loess samples having a same dry density. The increase of NaCl concentration in pore water can also lead to the decrease of shear strength of saturated loess, especially for the cohesion. The results of Scanning Electron Microscopy (SEM) tests gave a microscopic explanation for the above results. In conclusion, the enrichment of salt leads to the increase of water holding capacity of approximately saturated loess, which is closely related to the decrease of undrained shear strength in saturated conditions. This will help us to understand the mechanism of loess landslide in this area.

Keywords: NaCl, Loess landslide, chemomechanical behaviors, SWCC, sensitivity

1 INTRODUCTION

The chemomechanical behaviors of porous media is a major topic in soil mechanics (Nitaao and Bear,1996; Lu and Likos, 2006; Wei, 2014;). Pore water in soil is a complex chemical solution. As an active and sensitive factor in soil, the chemical composition of pore water is crucial to the mechanical strength of soils. The effect of pore water chemistry on the mechanical strength of soil has been investigated widely by previous studies. (Di Maio and Fenelli,1994; Tiwari et al.,2005; Naeini and Jahanfar, 2011; Thyagaraj and Rao,2013; Ismeik and Ashteyat, 2013; Zhang and Sun,2016; Ajmera and Tiwari,2018). In the above studies, it has been found that as the salt concentration of pore water solution alters, the surface potential of soil particles will alter accordingly, which led to the changes in the thickness of the diffusion double layer and in the strength of saline soil.

Heifangtai in Gansu Province (Figure 1), as the resettlement area of Liujiaxia Reservoir, has suffered from frequent loess landslides caused by large-scale agricultural irrigations, which has caused serious losses to the lives and property of local residents. As one of the most typical areas of irrigated loess landslides, it is known as "the microcosm of the loess plateau landslide geological disaster", and has been attracted by wide attention of scholars (Meng et al., 1998; Xu and Dai, 2014; Xu and Peng, 2016; Fan and Xu, 2017; Xu and Coop, 2017). Another characteristic of this area is the high salt content in the loess pore solution (Chen et al., 1999), as located in arid or semi-arid area. The decrease of saturated loess strength induced by irrigation is closely related to the migration and enrichment of soluble salts in loess. The chemomechanical properties of loess in this area have been studied in previous studies. For example, Li and Xu (2017) analyzed time effect characteristics of loess strength weakening by water, and discussed the influence of soluble salt content on the shear strength, collapsibility and other strengths of loess. Zhang et al.(2013) investigated the effects of NaCl concentration on pore water and desalinization on the shear behavior under undrained conditions by a series ring-shear tests on saturated loess.

The shear strength is the core index of loess landslide stability study (Stark 2013), which is affected
by loess density, water content, mineral composition, soluble salt content and gradation. Among all factors, water content, salt type and concentration are important.

Due to the long-term drought and lack of water in heifangtai area, agricultural irrigation mainly depends on pumping river water from the Yellow River. After that, irrigation water infiltrates through dominant channels such as joints, fissures and falling water tunnels in the loess, resulting in the rise of groundwater level in the deep soil layer (Xu and Dai et al., 2011a, 2011b; Xu and Peng et al., 2016). Water content has been identified as a key factor in influencing the shear strength of loess, for the inherent water sensitivity of loess (Zhang et al., 2016). Water infiltrates through the pores of the loess to a relatively impervious bed and causes the accumulation of groundwater level to rise, leading to the increase of loess saturation around the bed and the decrease of matrix suction. As the saturation of loess increases, a significant shrinkage phenomenon occurs because of the aggravation of plastic deformation. As a result, the soil pore water can’t be drained smoothly and pore pressure increases sharply to form static liquefaction. It causes a softening zone at the bottom of the loess. Meanwhile, undrained shear failure occurred in a short time, resulting in a sharp increase in deformation. A whole sliding forms as the sliding surface penetrates. This is the general mode of loess landslide failure in this area.

Salinity moves dynamically with water (rainfall or irrigation), and accumulates in the vicinity of the slip zone. So the loess is filled with highly saturated saline. Thus, the relationship between the chemomechanical behaviors of loess and the formation of landslides is worth further study. However, previous studies have focused on the unsaturated soils with low saturation, for which the electrochemical potential of pore fluids is affected chiefly by osmosis capillarity and adsorption. And only a few research studies have been performed to focus on the chemoplasticity of fully saturated soils (Huechel, 2002; Loret et al., 2004; Witteveen et al., 2013). As a matter of fact, landslide failure occurs principally under the condition of high saturation, thus, there is a clear need to develop the work in this field.

On the other hand, soil-water characteristic curve (SWCC) is a crucial tool to describe the flow and mechanical behavior of unsaturated soil, and becomes the link between the microscopic chemomechanical interaction and the macroscopic properties of soil (Fredlund and Xing, 1994; Thyagaraj and Rao, 2010), which can help us to understand the influence of chemical composition in soil pores on water retention performance. It has been found that the increase of salt content will lead to the increase of saturation in the boundary effect region from SWCCs of saline soils (Ma and Lin, 2013; Ma and Wei, 2015; He and Ye, 2016; Ma and Wei, 2017). Within this context, to shed new insights into the coupling effects of water-salt-strength, we investigated the influence of NaCl concentration on the loess shear strength, based on the results of NaCl concentration on loess water retention, and analyzed the possible mechanisms for the occurrence of loess landslides.

2 STUDY SITE

The study area is located in Yongjing County, Gansu Province (Figure 1). In terms of geological structural unit, it belongs to the Qilian Mountain geosyncline of the Qin-Qi-Kunlun geosyncline system. Strong tectonic activities destroyed the integrity of strata, surface water is easy to infiltrate and make the self-weight of slopes increase. At the same time, the river gradient of each river system in the basin increases, the erosion datum level decreases and the river cuts down, creating a favorable free surface for the formation of landslides.

The base of terrace IV where Heifangtai located, is the Lower Cretaceous Hekou Group, with the loose strata of the Upper Pleistocene overlying it (Wang and Wu et al., 2004; Xu and Peng et al., 2016) (Figure 2).

The Lower Cretaceous Hekou Group is composed of brownish red, fuchsia thick or thick silty mudstone with purple lime, purple-red sandstone and argillaceous
siltstone. The Upper Pleistocene strata are composed of alluvial sandy gravel, silty clay and aeolian loess. Aeolian loess covers the fourth terrace. The Aeolian Loess in Heifangtai is typical gray yellow named Malan with uniform structure, porous porosity and vertical joints, which softens rapidly in the presence of water. The general situation is that loess in east is thicker than that in the west, the loess in the south is thicker than that in the north. The loess in the western plateau with thick clay layers is thinner, and the loess in the southeastern plateau with thin clay layers is thicker.

As the obvious characteristics such as loose porous, vertical joints, collapsible cracks and falling water caves in thick loess, mudstone in the following is relatively impervious and pebble-gravel layer is porous. The loess located in arid or semi-arid area, so the pore solution has higher salt content (Chen et al., 1999). Salt in soil migrates with water because of rainfall or irrigation, as a result, a large amount of salt is released from the contact zone of loess and underlying bedrock (Figure 2). Precipitation of salt shows that the salt content in the loess exceeds the saturated concentration. The existence of supersaturated salt solution causes changes in the structure, material composition and particle size distribution of the loess, which lays a foundation for the large-scale loess sliding disasters.

3 TEST MATERIALS AND METHODS

3.1 Sample

![Grain size distribution curve of loess sample](image)

The loess samples were taken from the rear edge of Dangchuan No. 2 landslide in Heifangtai on April 29, 2015 (Figure 1). The basic physical and mechanical parameters are shown in Table 1. The grain size distribution curve (see Figure 3) of loess samples was measured by laser particle size analyzer (Malven MS-2000, UK). Chemical composition of the samples were analyzed by ion chromatograph (Dionex ICS-2500, USA). The results in Table 2 show that the soluble salt content of loess in this area is high, and is mainly NaCl type. From Table 2, it can be seen that relative to the slip body, the loess in the slip zone has little residual soluble salt after repeated leaching, which basically meets the test requirements.

We used remolded loess samples matched with different concentrations of NaCl solution, the concrete preparation scheme is as follows: Concentration of NaCl solution: As is known that the saturated concentration of NaCl solution is 5.43 mol/L, our target concentration is set as 0 mol/L, 1.0 mol/L, 3.0 mol/L, 5.0 mol/L and 10.0 mol/L. Hereinafter, we term these NaCl solutions with the concentrations being 0 mol/L, 1.0 mol/L, 3.0 mol/L, 5.0 mol/L and 10.0 mol/L as C0, C1, C3, C5 and C10, respectively.

| Property                      | Value     |
|-------------------------------|-----------|
| Specific gravity (Gs)         | 2.71      |
| Uneven coefficient(Cu)        | 12.5      |
| Curvature coefficient(Cc)     | 2.0       |
| Liquid limit (wt, %)          | 26.5      |
| Plastic limit (wp, %)         | 15.6      |
| Plasticity index (Ip)         | 10.9      |
| Optimal moisture content (wp, %) | 16.2 |
| Maximum dry density (ρd, kg/m³) | 1.74 |
| Soil classification           | Silty clay|

The initial moisture content of the prepared sample was set as around the plastic limit, that is, 18%; the dry density was set as 1.74 g/cm³, which is close to the maximum dry density. The preparation method and process are as follows: NaCl is mixed with degassed distilled water to form a solution of corresponding concentration. NaCl was thoroughly stirred and dissolved, then mixed with dry soil and sealed for more than one week. The soil samples prepared above were static compacted on both sides and saturated with NaCl solution of corresponding concentration.

| Sampling locations               | No. | Na⁺ (g/kg) | K⁺ (g/kg) | Mg²⁺ (g/kg) | Ca²⁺ (g/kg) | Cl⁻ (g/kg) | SO₄²⁻ (g/kg) |
|---------------------------------|-----|------------|-----------|-------------|-------------|------------|--------------|
| Natural loess near slipping zone| 1   | 42.26      | 0.39      | 2.58        | 12.61       | 40.42      | 14.82        |
| Natural loess on Sliding wall   | 2   | 3.78       | 0.22      | 0.28        | 4.14        | 0.21       | 0.75         |
| Leached Loess on Sliding wall   | 3   | 0.02       | 0.02      | 0.02        | 0.40        | 0.02       | 0.14         |

3.2 Test Methods

1. Soil-Water Characteristic Curve (SWCC)

In order to further understand of the SWCCs of saline soil, both the pressure plate apparatus method and filter paper method were employed to determine the SWCCs within the total suction range of loess.
samples.
(a) Pressure Plate Apparatus Test:
The soil-water characteristic pressure plate instrument applies suction to 700 kPa step by step (Chen and Liu, 2018). And SWCCs in this pressure range were obtained by reading the data after the equilibrium.
(b) Filter Paper Test:
The total suction was measured by non-contact method. Three soil samples in each group were air-dried to different degrees, and their moisture content ranged from 2% to 7%. They were put into wax-sealed boxes with filter paper. After two weeks, the volume, moisture content of soil samples and moisture content of filter paper were measured after the water balance between filter paper and soil sample completed. The filter paper used in the test is Double Circle No. 203 filter paper. The formula (formula (1)) for calculating the calibration curve is as follows (Tang and Li, 2016):

$$\gamma = \left( \frac{2.3026 - 0.0718 \theta}{0.01284 - 0.01818 \theta} \right) \leq 47$$

where $\gamma$ is the suction value, kPa; $\theta$ is the mass water content of filter paper (%).

According to the permeability suction proposed by Sun De'an (2013), as shown in formula (2), the matrix suction is calculated.

$$\theta_0 = \frac{vRTm}{\phi}$$

Where $v$ is the number of ions contained in salt molecule (e.g. for NaCl, $v=2$); $R$ is gas constant, 8.314462 J/(mol·K); $T$ is the degree kelvin(K); $m$ is the molar concentration, the molar number of solutes in 1 kg solvent; $\phi$ is the solution permeability coefficient, the permeability coefficients $\phi$ of NaCl solutions at different concentrations at 20 °C can be seen in Clarke and Glew (1985).

2. Saturated Undrained Shear Test
Samples were put into the shear box after saturated, and then the water-proof plates and permeable stones placed at both ends of the sample successively. Shearing tests were carried out at the shear rate of 0.04mm/min, after applying normal stresses of 100, 200, 300, 400 kPa respectively.

3. Scanning Electron Microscopy test (SEM)
The microstructures of the samples were analyzed by scanning electron microscopy test (SEM). The instrument model is Zeiss Auriga Compac(Germany). Before test, the samples need to be freeze-dried, conductive adhesive pasted and gold sprayed.

4 TEST RESULTS AND DISCUSSION
4.1 Analysis of water-retention of loess with different salt contents
The SWCCs of loess samples at different NaCl concentrations are presented in Figure 4. It can be observed that it has different characteristics for different stages of the SWCCs: ①In the boundary effect region affected by capillary action: with the increase of NaCl concentrations in the pore water, the water content of loess sample increases, and the SWCCs of different concentrations were almost parallel, which is basically consistent with previous research results (Thyagaraj and Rao, 2010; Ma and Lin, 2013; Ma and Wei, 2015; He and Ye, 2016). ②In the transition section of water film adsorption: with the increase of pore NaCl concentration, the curves moves up a little bit, which indicates that the existence of salt in soil pore solution makes the matrix suction of soil increase to a certain extent. ③In the residual region of solid adsorption: due to the loss of water, the salts dissolve out from pore water, pore solution gradually reaches to saturation, so the curves at this stage finally tend to be coherent. At the same time, it can be observed that the curves become steeper obviously when the suction is greater than 500 kPa, which is in accordance with the results reported by Madsen and Jensen (1986) and Campbell (1988). By Compared with the two parts SWCCs obtained by pressure plate method and filter paper method, we can find that the former is lower than the latter, which is mainly due to the poor continuity of water between soil sample and pressure plate under lower potential energy. So the balance process is very slow, which results in large error of pressure plate method (Madsen, 1986; Campbell, 1988).

![Fig.4 SWCCs under each NaCl concentration](image-url)

Previous researchers mainly focused on the influence of matrix suction, but neglected the osmotic suction. However, Miller et al. (2006) pointed out that osmotic suction can be affected by the salinity to some extent, but matrix suction is less affected, basing on their test results. The salt content in the soil was related to the permeability suction and had a low correlation with the matrix suction. Similar results have been obtained from the experimental study of silt by Sun et
The difference between the total suction and the matrix suction was greater than that of pure salt solution with the same concentration. The reason is caused by the adsorption action of soil particles to the solution. It has been also concluded that the matrix suction of saline soil is affected by the salt content by Wang and Dang (2009), Yu and Zhang (2013). Li and Zhou (2012), Guo and Wang (2014) have studied the effects of different concentration of pore solution on soil water retention curves, and found that the salinity of water had a certain effect on the saturated moisture content. In this study, the saturation of loess increases with the increase of salt content, under the same suction condition. The results are consistent with the above research results. It shows that the increase of salt content in loess leads to the increase of saturation. However, due to the close relationship between saturation and shear strength, it’s bound to cause the change of shear strength.

4.2 Undrained Shear Strength

Direct shear tests were employed for determination of undrained shear strength of remolded saturated-loess specimens at different salt concentrations. The stress-strain curves are presented in Figure 5(a)–(e). As can be seen from the figures, with the increase of NaCl concentration, the strain hardening phenomenon of the samples becomes more and more obvious, especially for samples of C5 and C10 (corresponding NaCl concentration is 5.0mol/L and 10.0mol/L, respectively).

Figure 6 (a)–(d) present the stress-displacement curves of specimens with different NaCl concentrations under different normal stresses ($\sigma_n=100$ kPa, 200 kPa, 300 kPa and 400 kPa, respectively). With the increase of NaCl concentration, the undrained shear strength of the specimens decreases slightly compared to the original soil samples, with a decrease of 5.78%–12.65%. This phenomenon is obvious especially as the normal stress level $\sigma_n=100$ kPa and $\sigma_n=400$ kPa.

Figure 7 shows the relationship between normal stress and shear strength of specimens with different concentrations. The index C and $\phi$ have been calculated according to the Mohr-Coulomb criterion (as shown in Figure 8), and the cohesion C and internal friction angle $\phi$ show a decreasing trend. The decrease on the internal friction angle $\phi$ is relatively small. But it’s greater for C value, even negative. This can be explained by the concept of real pore water pressure proposed by Wei (2014), that is, cohesion at this condition including osmosis pressure (Warkentin, 1962; Naeini, 2011; Yu and Wei, 2015).
The influence of NaCl concentration on soil strength is attributed to the influence of hydrochemical state on soil strength, which can be explained by the double layer theory of adsorption electron (Mitchell, 1993). However, the soil structure should be also considered. Shear strength is directly related to soil structure besides the change of salinity. It is important to note that the dry density obtained by field test is adopted in this study, that is, the initial pore structure of the sample is the same.

Fig. 6 Shear stress-shear displacement curves under each normal stress

When the pore solution changed from water into salt solution, the ion concentration increases, which makes the soil particles surface potential increased and ion diffused in fluid, thus the osmotic repulsion force reduced, and the effective positive stress increased. As a result, the thickness of the diffusion double layer gets thinner. Meanwhile, as for the repulsion force between particles decreases, and the attraction plays a dominant role, the granule will shrink, leading to the enlargement of intergranular porosity (Wang and Fu, 2009; Zhang and Wang, 2013; Yan and Liang, 2017). On the one hand, more water is filled in the limited space, that is, the degree of saturation increases. On the other hand, more macropores are formed inside the soil, and the structure is looser. The interaction of the two factors decreases the shear strength of the soil.

4.3 Results of microscopic tests

The complex physical and mechanical properties of soils depend on their microstructure characteristics essentially. It plays an important role in understanding the macroscopic behaviors and chemomechanical mechanism of pore solution influencing the change of strength characteristics.

SEM tests were employed to analyze the effect of NaCl concentration on the microstructure of loess samples. It can be seen from Figure 9(a)-(f) that when NaCl concentration increases, larger aggregates or...
clusters have been formed among the soil particles, which results in changes in surface roughness and specific surface area of the soil particles. With the increase of NaCl concentration, the surface of soil particles is gradually covered with a layer of salt crystals of different degrees and forms. At a concentration of 1 mol/L, discrete crystals are formed. With the increase of NaCl concentration, salt crystals are connected piece by piece, filling and wrapping in gaps between soil particles, and even forming clusters. Once the clusters formed, larger pore spaces will form, thus microstructures of samples will change. At this point, the shear behavior of the sample will be dominated by the shear failure of aggregate clusters, and the soil strength with larger aggregates will be weakened.(McDowell and Bolton, 1998; Iverson et al., 2010; Yan & Liang, 2017). Meanwhile, the increase of salt concentration in pore solution will cause ion diffusion in the fluid, and Na\(^+\) and Cl\(^-\) exhibit different movement characteristics in this process of migration: cationic Na\(^+\) is easy to migrate with water and enrich on the surface of soil particles, however, negative ion Cl\(^-\) is relatively not easy to migrate, but it can increase the intergranular coupling.

In this study, we started with the perspective of suction, and focused on the loess saturation changes affected by different salt concentrations under the same suction condition at the low suction stage, that is, the increase of salt content causes the increase of saturation under the same suction condition, and the enrichment of salt causes the changes in the size of of clay particles in the soil, and the formation of larger aggregates or aggregates, which are corresponding to the SEM result. Meanwhile, the increase of aggregates and aggregates with larger grain size leads to the change of loess pore structure, which is one of the internal mechanisms of loess strength decrease.

5 CONCLUSION

In this paper, loess samples were saturated with NaCl solution at different concentrations, and the initial dry density of remolded loess samples were the same to each other. SWCC, undrained shear strength and microstructure of the samples were obtained. The conclusions were drawn as followings:

1) NaCl content has a certain impact on matrix suction, i.e., as for the same matrix suction, the mass water content increases along with the increase of NaCl solution concentration, especially near the stage of fully saturation. The maximum value can reach to 8.5%-18.8%, especially for C10, the incremental amount to 42.9%. The difference gradually decreases and tends to be consistent from the boundary effect zone to the transition zone.

2) The undrained shear strength of the tested loess decreases with the increase of NaCl concentration., and the strength decreases along with the increase of salt solution concentration under the same normal stress, i.e. the cohesion and friction angle decreases in some extent.

3) Miroscopic SEM results show that, the chemical action of soil-water changes microscopic structure of the loess, thus affects the water retention capacity, which is the essential reason for the decrease of loess strength.

4) The enrichment of soluble salts leads to the increase of saturation (near the fully saturation) of the sliding soil, which results in the decrease of shear strength. This is intimately related to the trigger of landslide disasters. The undrained shear strength of saturated loess decreases with the increase of salt content, which indicates that the loess landslides is more sensitive to enrichment of salt.

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REFERENCES

1) Ajmera, B., Tiwari, B. and Ostrova F. (2018): Influence of Salinity of Pore Fluid on the Undrained Shear Strength of Clays[C]// Ifcee.
2) Campbell, G. (1988): Soil water potential measurement: An overview, Irrigation Science,9(4):265-273.
3) Chen, W., Liu, W., and Wang J. (2018): Prediction and analysis of permeability coefficient of unsaturated loess with different permeability duration, Journal of Geotechnical Engineering, 40(suppl.1): 22-27. (in Chinese)
4) Chen, J., Han, Q. and Li, B. (1999): Land surface settlement, soil loss and corresponding dismiss in Heifangtai Irrigation area in Yongjing County, Soil and Water Conservation in China,(4): 15-17 (in Chinese)
5) Clarke, E. C. W. and Glew D. N. (1985): Evaluation of the thermodynamic functions for aqueous sodium chloride from equilibrium and calorimetric measurements below 154°C, Journal of Physical and Chemical Reference Data,14(2): 489-610.
6) Di Maio, C., and Fenelli, G. B. (1994): Residual strenght of kolim and bentonit: the influence of their constituent pore fluid,Geotechnique, 44(2): 217-226.
7) Fan, X., Xu Q. and Scarinci G(2017): A chemo-mechanical insight into the failure mechanism of frequently occurred landslides in the Loess Plateau, Gansu Province, China, Engineering Geology, Engineering Geology, 228: 337-345.
8) Fredlund, D. G., Xing A. Q.(1994): Equations for the soil-water characteristic curve,Canadian Geotechnical Journal, 31(4): 521-532.
9) Guo, Q., Wang Y. and Nan L.(2014): Effect of solute type and salinity on soil water retention curve, Chinese Journal of Soil Science,45(2): 340-344. (in Chinese)
10) He, Y., Ye, W. and Chen, Y. (2016): Influence of pore fluid concentration on water retention properties of compacted GY01 bentonite,Applied clay science, (129):131-141.
11) Hueckel, T.(2002): Reactive plasticity for clays during dehydration and rehydration. Part 1: Concept and options, Int. J. Plast,18:281-312. doi:10.1016/S0749-6419(00)000099-1.
12) Ismeik, M., Ashayeay, M. A. & Ramadan, Z. K. (2013): Stabilisation of fine-grained soils with saline water, European Journal of Environmental and Civil Engineering, 17:1,32-45. DOI: 10.1080/19648189.2012.720399.
13) Iverson, N.R., Mann, J.E., Iverson, R.M. Effects of soil aggregates on debris-flow mobilization: results from ring-shear experiments[J]. Engineering Geology, 2010,114, 84-92.
14) Li, S., Xu, Q., Zhang L., et al. (2017):Time effect characteristics and mechanism analysis of loess strength weakening by water in Heifangtai area,Chineses Journal of Rock and soil mechanics,38(7):2043-2048. (in Chinese)
15) Li, X. , Zhou, J., Jin, M., et al.(2012):Soil-water characteristic curves of high-TDS and suitability of fitting models,Transactions of the Chinese Society of Agricultural Engineering, 28(13): 135-141. (in Chinese)
16) Lorent, B., Gajo, A. and Simões F. (2004): A note on the dissipation due to generalized diffusion with electro-chemo-mechanical coupling in heterionic clays, Eur. J. Mech. Solids 23:763-782. doi:10.1016/j.euromechsol.2004.04.004.
17) Lu, N. and Likos W. J. (2006): Suction stress characteristic curve for unsaturated soil, Geotech. Geoenviron. Eng., 132(2): 131-142. doi:10.1061/(ASCE)1090-0241(2006) 132:2(131).
18) Ma, K. , Lin Y., Tan Y. (2013):The influence of salinity on hysteresis of soil water-retention curves,Hydrological Processes,27(17):2524-2530.
19) Ma, T., Wei C. and Chen, P. (2015): Experimental study on the influence of NaCl solution on soil moisture retention characteristics,Rock and soil mechanics,36(10):2831-2836. (in Chinese)
20) Ma, T., Wei, C., et al.(2017): Soil freezing and soil water retention characteristics: connection and solute effects, Journal of performance of constructed facilities,31(1): D4015001.
21) Madsen, H. B., Jensen C. R. and Boysen T.(1986): A comparison of the thermocouple psychrometer and the pressure plate methods for determination of soil water characteristic curves,Journal of Soil Science,37(3):357-362.
22) McDowell, G. R., Bolton, M. D.(1998): On the micromechanics of crushable aggregates, Geotechnique, 48, 667-679.
23) Meng, X., Derbyshire, E.(1998):Landslides and their control in the Chinese Loess Plateau: models and case studies from Gansu Province,China, Geological Society.London, Engineering Geology Special Publications,15(1):141-153.
24) Mitchell, J. K. (1993): Fundamentals of soil behavior. New York: Wiley.
25) Miller, D. J., Nelson, J. O. Osmotic suction in unsaturated soil mechanics[C]// Fourth International Conference on Unsaturated Soils. Arizona, USA: [s. n.], 2006: 1382-1393.
26) Naeini, S. A., Jahanfar, M. A. (2011): Eeffect of salt solution and plasticity index on undrain shear strength of clays,World Academy of Science, Engineering and Technology, 49: 982–986.
27) Nitao, J. I. and Bear, J.(1996): Potentials and their roles in transport in porous media, Water Resour. Res.,32(2):225-250. doi:10.1029/95WR02715.
28) Sun, D., Zhang, J. and Song, G. (2013): Experimental study of soil-water characteristic curve of chloride saline soil, Rock and Soil Mechanics,34(4):955-960.
29) Stark, T. D., Hussain, M. (2013): Empirical Correlations: Drained Shear Strength for Slope Stability Analyses, Journal of Geotechnical & Geoenvironmental Engineering, 139(6): 853-862.
30) Tang, D., Li, D., KIM Ho-et al.(2016): Research on calibration curves of home-made “Double Circle” filter papers, Engineering Journal of Wuhan University, 49(1): 1-8. (in Chinese)
31) Tiwari, B., Tuladhar, G. R. and Marui, H. (2005):Variation in Residual Shear Strength of the Soil with the Salinity of Pore Fluid, Journal of Geotechnical & Geoenvironmental Engineering, 131(12):1445-1456.
32) Thiyagaraj, T., Rao, T. T.(2010): Influence of osmotic suction on the soil water characteristic curves of compacted expansive clay, Geotech Geoenviron Eng ASCE 136(12):1695-1702.
33) Thiyagaraj, T., Rao, S. M.(2013): Osmotic swelling and osmotic consolidation behaviour of compacted expansive clay, Geotech Geol. Eng.,31(2):435-445.
34) Xu, L., Dai, F. and Tham, L.G.,et al.(2011a): Field testing of irrigation effects on the stability of a cliff edge in loess, North-west China. Engineering Geology 120(1),10-17.
35) Xu, L., Dai, F. and Gong, Q.(2011b): Irrigation-induced loess flow failure inHeifangtai Platform, North-West China. Environ. Earth Sci. 66, 1707-1713.
36) Xu, L., Dai, F.,Tu, X.,et al.(2014): Landslides in a loess
37) Xu, L., Coop, M. and Zhang, M. (2017): The mechanics of a saturated silty loess and implications for landslides, Eng. Geol., 1-14.http://dx.doi.org/10.1016/j.enggeo.2017.02.021

38) Xu, Q., Peng, D., Qi, X. et al. (2016): Study on the basic characteristics and mechanism of Dang Chuan landslide No.2, Heifangtai, Gansu province on April 29, 2015, Chinese Journal of Engineering Geology, 24(2): 167-180. (in Chinese)

39) Yan, R., Liang, W., Yang, D., et al. (2017): Effect of sodium chloride solution on clay strength, Journal of Geological Hazards and Prevention, 15(3): 43-46, 54. (in Chinese)

40) Wang, L. (2003): Loess Dynamics. China Beijing: Earthquake Press, 10. (in Chinese)

41) Wang, L., Dang, J. and Yang, X. (2009): The research of soil-water characteristic curves of saline soil, Geotechnical Investigation & Surveying, 37(2): 19-23. (in Chinese)

42) Zhang, F., Wang, G., Kamai, T., Chen, W., et al. (2013): Undrained shear behaviour of saturated loess at different concentrations of sodium chlorate solution, Engineering Geology, 155, 69-79.

43) Zhang, L., Sun, D., Jia, D. (2016): Shear strength of GMZ07 bentonite and its mixture with sand saturated with saline solution, Applied Clay Science, 132-133: 24-32.

44) Wang, L. (2003): Loess Dynamics. China Beijing: Earthquake Press, 10. (in Chinese)

45) Wang, L., Dang, J. and Yang, X. (2009): The research of soil-water characteristic curves of saline soil, Geotechnical Investigation & Surveying, 37(2): 19-23. (in Chinese)

46) Zhang, M., Hu, W., Sun P., et al. (2016): Research status and prospect of loess water sensitivity and water-induced loess landslide, Chinese Journal of Earth Environment, 7(4): 333-334. (in Chinese)

47) Wang, Z., Wu, W. and Zhou, Z. (2004): The landslide disaster caused by excessive agricultural irrigation in loess tableland of Gansu province, Chinese Journal of Geological Hazards and Prevention, 15(3): 43-46, 54. (in Chinese)

48) Markentin, B. P., Yong, R. N. (1962): Shear strength of montmorillonite and kaolinite related to interparticle forces, Clays and Clay Minerals, (9): 210-218.

49) Wei, C. (2014): A theoretical framework for modeling the Chemo-mechanical behavior of unsaturated soils, Vadose Zone Journal, 13(9): 1-21.

50) Witteveen, P., Ferrari, A. and Laloui. L. (2013): An experimental and constitutive investigation on the chemo-mechanical behavior of a clay, Geotechnique 63(3): 244-255. doi: 10.1680/geot.13.P.027.