KSCE Journal of Civil Engineering (2018) 22(11):4373-4384

DOI 10.1007/s12205-017-0170-4

Structural Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Experimental Investigation of the Behavior of Collapsible Loess Treated with the Acid-addition Pre-soaking Method

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Received February 6, 2017/Accepted March 9, 2018/Published Online October 11, 2018

Abstract

The pre-soaking method is widely used to address loess collapsibility. However, this method requires a long construction time and has a limited application range. To foster the strengths and avoid the weaknesses of the pre-soaking method regarding ease of use, acid-addition collapsibility tests and acid-addition shear tests were performed to investigate the effect of combining the pre-soaking method with the use of an acetic acid solution. This approach is based on the principle that acid can dissolve cemented connections, which is the main factor of loess collapsibility, in a short period of time. Moreover, a Scanning Electron Microscope (SEM) was used to observe the features of loess samples before and after these tests. The SEM images also confirm our inferred conclusions. The experimental results showed that, compared with the conventional pre-soaking method, the addition of acetic acid sharply decreases the loess collapsibility under low pressure condition and reduces the construction time. In addition, the proposed approach simultaneously increases the strength of modified soil under low pressure conditions. Further, the addition of acetic acid allows the pre-soaking method to be applied to a non-self-weight collapsible loess, to which the conventional pre-soaking method cannot be applied.

Keywords: *calcium carbonate cementation, acid-addition collapsibility tests, acid-addition shear tests, scanning electron microscope, non-self-weight collapsible loess*

1. Introduction

Quaternary deposits of loess are widely distributed, accounting for approximately one-tenth of the Earth's land area (Dudley, 1970; Kim and Kang, 2013). China is home to the widest and thickest loess deposits in the world; the area covered by loess in China is greater than 630,000 square kilometers (Derbyshire *et al*., 1995; Gao, 1996; Nouaouria *et al*., 2008; Liang *et al*., 2016). Chinese loess is mainly distributed in the Loess Plateau of the Northwestern Territories, the Northern Plain of China and southern part of Northeast China (Fig. 1). Loess has a particular interior material composition, structure and external morphology, making it different from other sediment deposits of the same age, i.e., its collapsibility (Collins and Mcgown, 1974; Delage *et al.*, 2005; Kim and Kang, 2013; Lv *et al*., 2014; Zhang *et al*., 2017). Unfortunately, the collapsibility of loess can pose serious problems, including large-area cracking, subsidence of the foundation sub-grade, tilting and collapse of high buildings, to construction projects built on loess foundations (Buscarera and Prisco, 2013; Gibbs and Holland, 1960; Mihalache and Buscarnera, 2015; Rogers *et al*., 1994). To counteract these unfavorable engineering properties of collapsible loess, engineers have used a variety of foundation treatment techniques, such as the cushion technique, dynamic compaction technique, compaction pile technique, pile foundation treatment and pre-soaking method. The cushion and dynamic techniques compaction effectively eliminate the collapsibility of shallow soil; however, the desired effect is often not achieved with thick collapsible loess (Feng *et al*., 2015; MHURDPRC, 2012). In modern times, addressing the issues associated with thick collapsible loess is a popular topic of study in the geotechnical engineering domain and in academic research. The measures that are often applied to address these issues are the pile foundation treatment method and compaction pile method (Yu *et al*., 2013). However, these methods are difficult to implement in many projects because of their high cost. By contrast, the pre-soaking method has the advantages of simplicity and low cost and can be performed effectively in thick and deep soils (Wang *et al.,* 2014).

Many scholars have been working to improve the pre-soaking method to make it more broadly applicable, more efficient, and more economical. This method was first applied in the Golodnaiyad Prairie in Russia in 1914-1915 (Jefferson *et al.*,

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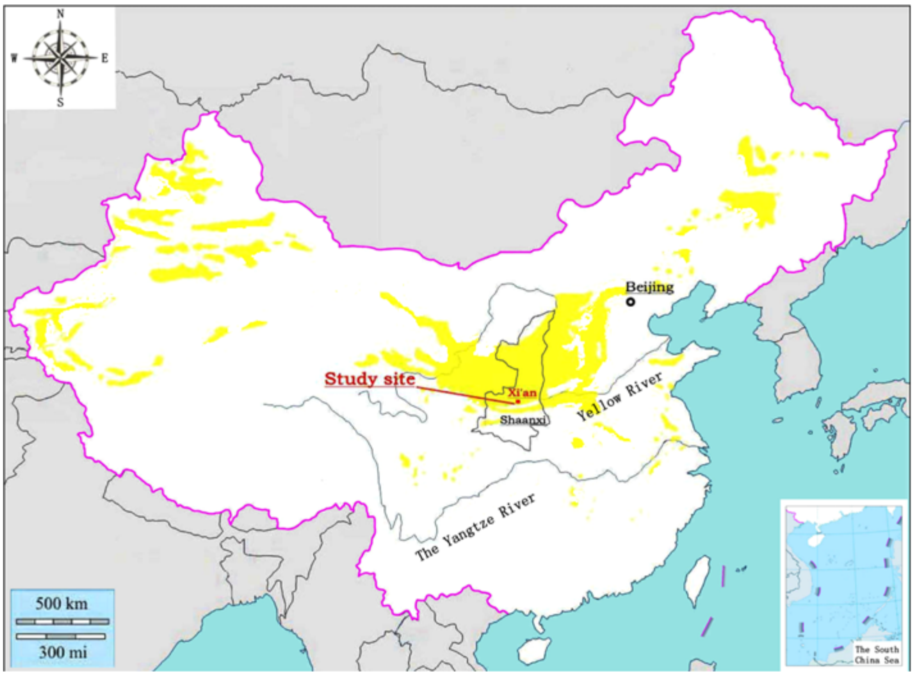

Fig. 1. Loess Distribution in China

2005). Subsequently, the method was used to treat the foundation of the American Medicine Creek Dam in 1958 (Beles *et al*., 1969), followed by its use in Ukraine, Bulgaria and other countries. This method has consistently shown good effects (Jefferson *et al*., 2005). Combining the pre-soaking technique and blasting greatly improved the pre-soaking method in two different approaches. One approach involves surface blasting, which has been applied in irrigation projects in the former Soviet Union as well as in hydraulic architecture in Bulgaria (Askarov *et al.*, 1981; Jefferson *et al.*, 2005). The other approach involves deep blasting. In 1964, the Soviet Union successfully used this method to eliminate loess collapsibility for a period of one year (Huang and Yang, 2013). Compared with the conventional method of pre-soaking, the joint application method requires less water and reduces the soaking time; however, construction under this method is slightly more complex, and the cost is higher (Jefferson *et al*., 2005). The Chinese began to study of field immersion tests in the 1960s, with many outstanding achievements since then (Huang and Yang, 2013). By combining the pre-soaking method with a soil cushion and blasting the expanded pile, Liao ShengXiu successfully addressed 14 large thick collapsible loess foundations at the Liancheng Aluminum factory in Lanzhou City, Gansu Province in 1968. However, the cost was quite high. Liu BaoJian used Time-Domain-Reflectometry (TDR) with the pre-soaking method. Wang XiaoJun conducted field immersion tests on several sites of the Zhengzhou-Xi'an Passenger Dedicated line and offered optimization foundation treatment proposals. These approaches allowed for greater diversity and accuracy of the pre-soaking method; however, they did not significantly improve the construction effects.

To make the pre-soaking method more efficient, collapsibility tests and shear tests were conducted by using appropriate amounts of acid to investigate the effect of the pre-soaking method combined with the use of acid in water (hereafter, referred to as the "acid-addition pre-soaking method"). The theory behind this novel method is that, with the help of acid, calcium carbonate cementation in loess can be dissolved faster and more easily. Thus, the macropores structure of loess is destroyed more easily, and collapse occurs completely and quickly. Acetic acid was chosen as the additive because of its benign nature, as it is the main raw material of vinegar. The experimental results proved that the acid-addition pre-soaking method can better eliminate the collapsibility of loess and reduce the operating time. Furthermore, this method is suitable for use in non-self-weight collapsible loess.

This study consists of 3 parts. First, to imitate the pre-soaking method to the greatest extent in the laboratory, collapsibility tests under different pressures with different concentrations of acetic acid in immersed water were performed. The collapse potential (I_c) (ASTM, 2003), stability time of the collapse, saturation defromation, collapse rate and other important indicators of loess collapsibility were observed and analyzed to investigate the performance of the acid-addition pre-soaking method. Second, as the mechanical property of soil after construction is of great importance for the superstructures, shear tests were performed to investigate the strength of the soils after construction by using this method. The soil samples were, initially, consolidated under different pressures in different solutions for three days, and then, quick direct shear tests were conducted. The mechanical indicators of the modified soil, i.e., cohesion, friction angle and shear strength were observed and analyzed. Third, to obtain more in-depth analysis and more compelling scientific results, SEM tests were performed. The microstructures of the loess samples before and after the tests were observed to validate our research findings (Barden *et al.*, 1973; Cheng *et al*., 2013; Collins and Mcgown, 1974; Dinh *et al*., 2012; Zuo *et al.*, 2016).

2. Materials Preparation and Characterization

2.1 Specimen Preparation and Characterization

2.1.1 Specimen Preparation

Test samples were taken from a construction pit in the northern suburb of Xi'an, the depth of which was 3.8-4.5 meters (Fig. 2). The loess belongs to the Malan loess, and the collapsible coefficient was 0.062, indicating medium collapsibility. The samples were cut to be approximately 40 cm × 40 cm × 40 cm in size from the foundation pit, and then, the top and the bottom positions were indicated, followed by transportation of the samples to the laboratory while avoiding disturbances. In the laboratory, the samples were shaped using ring knifes to a diameter of 8 cm and height of 2 cm for collapsible tests and a diameter of 6 cm and height of 2 cm for the shear tests.

The specimens for the SEM tests were prepared as follows. The loess samples were pressurized to pressures at 50, 200 and 800 kPa and then immersed in the corresponding reagents (distilled water, 1 mol/L and 2 mol/L acetic acid solution) for 3 days. These samples together with one undisturbed soil sample were air-dried for 2 weeks and then cut such that the diameter was smaller than 8 mm and height was between 8 mm and 13 mm (Fig. 3). To obtain clear images for SEM analysis, all of the samples were placed in a gold plating instrument to be coated with gold to a thickness of 10 nm over 180 seconds. The instrument is made by the Japanese manufacturer-JEOL in Japan, the model was JFC-1600.

Fig. 2. (a) Wide View; (b) Close-up View Sampling Site

2.1.2 Specimen Characterization

Table 1 lists the physical properties of the natural loess. According to the loess classification suggested by Gibbs and Holland (1960), which is based on the plasticity index (I_P) and

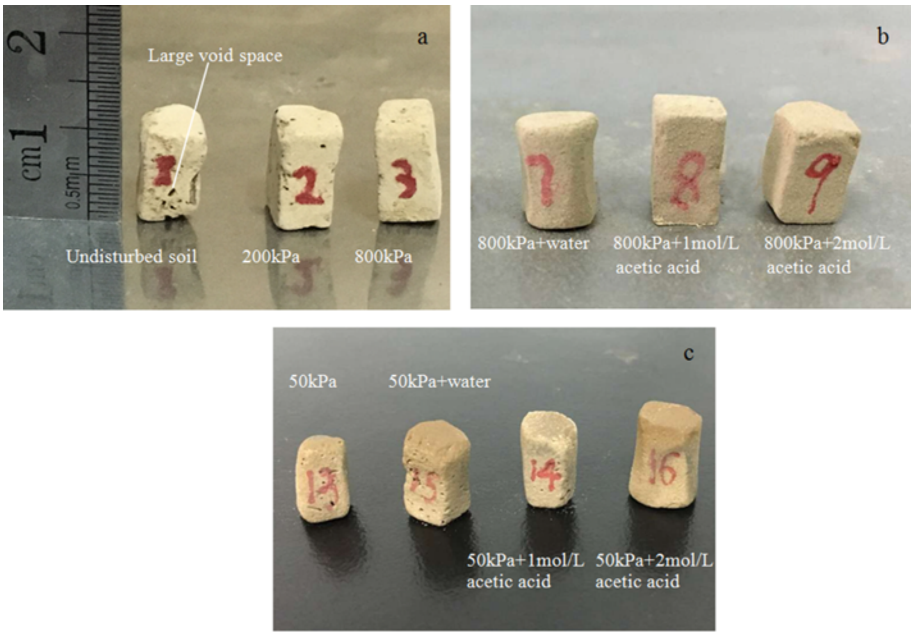

Fig. 3. Samples for SEM Imaging under Conditions of: (a) Different Pressures before Flooding, (b) 800 kPa Pressure and Different Concentration Solutions, (c) 50 kPa Pressure and Different Concentration Solutions

Table 1. Average Soil Characteristics

ρ_s (g/cm^3)	ρ (g/cm^3)	w (%)	e	W_L (%)	W_P (%)	I_P (%)	$CaCO_3$ (%)	Percent finer by weight (%)		
								>0.05	0.05-0.005	<0.005
2.71	1.51	15.1	1.08	29.94	19.66	10.28	11.22	35.49	60.88	3.63

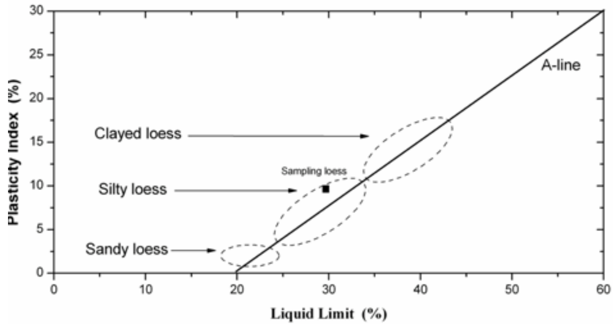

Fig. 4. Categorization of Loess According to the Plasticity Properties Suggested by Gibbs and Hliiand (1960)

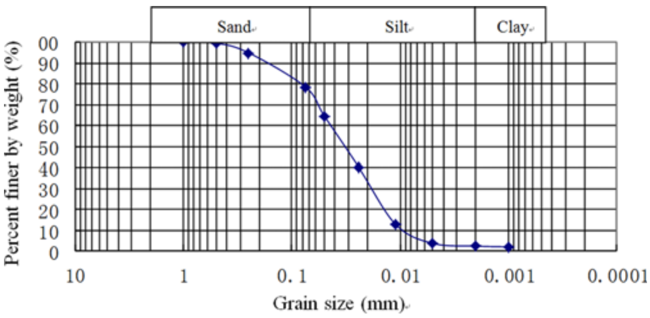

Fig. 5. Grain Size Distribution of a Loess Sample

liquid limit (W_l), the loess was in the scope range of silt loess (Fig. 4). Silt loess is inorganic soil of low plasticity. This soil is generally sensitive to changes in the moisture content. It was evident that the $CaCO_3$ content of natural loess was high, which resulted in a high void ratio and low density (Liu, 1997; Gao and Gao, 1960; Gao, 1961). However, the EDAX data and figures of the soils, which are not presented in this paper, showed that the content of calcium dropped from 4.12% before acid-soaking to approximately 2.4% after acid-soaking, confirming that it was possible for the natural loess to be further compressed using the acid-addition pre-soaking method.

The grain size results are shown in Fig. 5. The dominant size fraction of the natural loess was silt (0.002-0.06 mm) (accounting for up to 71% of the loess), which had poor mechanical quality, such as liquidation and collapsibility (Nouaouria *et al.*, 2008). Clay only accounted for 2.33%.

2.2 Solutions Preparation and Characterization

2.2.1 Solutions Preparation

Acetic acid solutions were prepared at four concentrations, 0.5 mol/L, 1 mol/L, 1.5 mol/L, and 2 mol/L, and then used to soak the soils for 3 days. Next, the filtering liquid of the immersed soils was collected by a funnel with filter paper. A pH meter was used to measure the pH value before and after these tests.

Table 2. PH Value of the Solutions before and after the Tests

The concentration of acetic acid	0.5 mol/L	1 mol/L	1.5 mol/L	2 mol/L
Before the tests	3.23	2.68	2.52	2.44
After the tests	5.22	5.05	4.77	4.65

Table 2 shows the pH value of the solutions before and after the tests. The pH values of the solutions before the tests ranged from 2.44 to 3.23, and those after the tests ranged from 4.65 to 5.22 (the pH of vinegar is approximately 3, and the pH of groundwater is always 5-8). The results were found to be acceptable, and eventually, concentrations of 1 mol/L and 2 mol/L acetic acid were found to be preferable to perform the tests.

(Note: When implementing the acid pre-soaking method in the field, it is necessary to sample soils in situ to test the initial contents of soluble salts. Next the type and amount of added acid is adroitly determined according to the amount of soluble salt in the loess, thickness of the collapsible loess, and quality standards of ground water and soils from different countries.)

2.2.2 Solutions Characterization

Acetic acid was chosen as the additive to perform our tests because of its benign nature. When the acetic acid solution infiltrated the soils, it reacted with the soluble salts of loess to form acetates. Most acetates are safe and can be used in drugs or food preservatives. Eq. (1) shows the chemical reaction of acetic acid with calcium carbonate, which accounted for more than ninety percent of the soluble salts in the loess and was the main cause of pore structure of loess.

$$2CH_3COOH + CaCO_3 = (CH_3COO)_2Ca + H_2O + CO_2\uparrow \quad (1)$$

The reaction products of acetic acid and calcium carbonate are calcium acetate, water and a small amount of carbon dioxide. Calcium acetate is frequently used as a food preservative and stabilizer, because of its excellent hygroscopic property. In addition, oxalic acid and phosphoric acid are also optional additives. Oxalic acid is a strong organic acid and is widely found in plant-derived foods. The acidity of oxalic acid is 10,000 times higher than that of acetic acid. Phosphoric acid, a medium strong acid, is a common inorganic acid. One of the reaction products of phosphoric acid and calcium carbonate is calcium phosphate, which is frequently used as a fertilizer and feed additive of livestock.

3. Experimental Methods

3.1 Loess Collapsibility Tests with Different Acetic Acid Concentrations

Table 3 shows the method of the Odometer tests (OW). Twenty-one loess samples were equally divided into three groups and then loaded at pressures of 25, 50, 100, 200, 400, 800, and 1600 kPa. When the conditions of the compression mentioned above were stable at all levels (compression for 24 hours), the samples were separately inundated with distilled water and, 1 mol/L and 2 mol/L acetic acid. Deformations of the samples were recorded at intervals of 0.10 (6 s), 0.25 (15 s), 0.5 (30 s), 1.00, 2.25, 4.00, 6.25, 9.00, 12.25, 16.00, 20.25, 25.00, 30.25, 36.00, 42.25, 49.00, and 64.00 min and then once every 30 min until the conditions were stable, namely, the deformation was less than 0.01 mm every hour (MWRPRC, 1999). When the conditions were stable, the loads were progressively increased to 1600 kPa, and the deformations were recorded in the same manner as in the previous steps. Another Compression Test (CT), as a baseline, was performed on a sample subjected to the same load to explore the compression properties of the soil.

3.2 Consolidation Quick Direct Shear Tests

Table 4 shows the method of the shear tests. Twelve loess samples were equally divided into three groups and then inundated with distilled water and 1 mol/L and 2 mol/L acetic acid from the water channel for three days; subsequently, the samples were lightly loaded with pressures at 50, 100, 200, and 400 kPa. When the consolidations were stable (the vertical deformation was less than 0.005 mm every hour), the samples were cut at a rate of 1.2 mm/min. A dynamometer reading of 4 mm corresponding to the shear stress was regarded as the shear strength (ASTM, 2011; MWRPRC, 1999).

Table 3. Program of Odometer Tests

Specimen	Test No.	Stress paths
Odometer tests in distilled water (OW0), 1 mol/L acetic acid (OW1), 2 mol/L acetic acid (OW2).	OW0/1/2 -1	L(25)/W/L (50,100,200,400,800,1600)
	OW0/1/2 -2	L(50)/W/L(100,200,400,800,1600)
	OW0/1/2-3	L(100)/W/L(200,400,800,1600)
	OW0/1/2- 4	L(200)/W/L(400,800,1600)
	OW0/1/2- 5	L(400)/W/L(800,1600)
	OW0/1/2- 6	L(800,)/W/L(1600)
	OW0/1/2- 7	L(1600)/W
Compression test	CT	L(25,50,100,200,400,800,1600)

Note: OW: odometer test, CT: compression test. The sample was subjected to a vertical step loading up to a specific value (symbolized as L), and the values of applied vertical pressure (kPa) are shown inside the subsequent parentheses. The sample was then wetted to saturation under a specific loading (symbolized as W), and the vertical loading was increased again (symbolized as L).

Table 4. Program of CQ Tests

Specimen	Test No.	Vertical stress (kPa)
CQ tests in distilled water (CQ0), 1 mol/L acetic acid (CQ1), 2 mol/L acetic acid (CQ2).	CQ0/1/2 -1	50
	CQ0/1/2 -2	100
	CQ0/1/2 -3	200
	CQ0/1/2- 4	400

Note: CQ, consolidated quick shear test.

3.3 SEM Tests

The samples prepared as described above were each placed on the chassis of a Merlin Compact SEM instrument (produced by Germany manufacturer-Carl Zeiss) using electrically conductive tape. Images were taken at 50, 100, 200, 500, 1000, and 2000 times magnification to investigate the changes in the aggregates and void space under different conditions. In this paper, because of limited space, only typical images were highlighted to confirm our arguments.

4. Results and Discussions

4.1 Comparison of the I_c in Distilled Water

The collapsibility of loess is typically measured and evaluated using the I_c (ASTM, 2003). Collapsibility is defined as the ratio of the height difference of a soil sample before and after soaking compared to the original height under a certain pressure, as given by Eq. (2).

$$I_c = \frac{h_p - h'_p}{h_0} \tag{2}$$

where h_0 is the original height of the sample (mm), h_p is the height of the sample that is stably compressed under a certain pressure (mm), and h'_p is the height of the stable sample under certain pressure, that remains stable when soaking (mm).

Table 5 shows the physical parameters of the soil samples during the compression test. The dry density, void ratio and compressibility coefficient slightly changed from 25 kPa to 200 kPa; subsequently, they markedly changed, reaching 1.40, 0.94 and 0.069, respectively, at 400 kPa, and then they gradually reached peak values of 1.89, 0.43 and 0.312, respectively, at 1600 kPa. Fig. 6 shows that the collapsible deformation in distilled water increased from 25 kPa to 400 kPa, whereas it decreased from 400 kPa to 1600 kPa. These two tests are routine tests and have the same results as those reported in other studies (Jiang *et al*., 2012; Munoz-Castelblanco *et al*., 2011). The reason for this phenomenon is as follows. Before soaking, the matric suction is high enough and cementation strength is sufficient to maintain the upper load between 25 kPa and 400 kPa; therefore, the loess samples could not be fully compressed. However, during flooding, the concentration of acetic acid in pore fluid is lower than that in the inundating fluid, resulting in outward

Table 5. Physical Parameters of CT Soil Sample

P/kPa	25	50	100	200	400	800	1600
ρ_d/(g.cm^{-3})	1.32	1.32	1.33	1.34	1.40	1.61	1.89
e/%	1.06	1.05	1.03	1.02	0.94	0.68	0.43
δ/%	0.011	0.015	0.022	0.028	0.069	0.193	0.312

Note: δ, coefficient of compressibility.

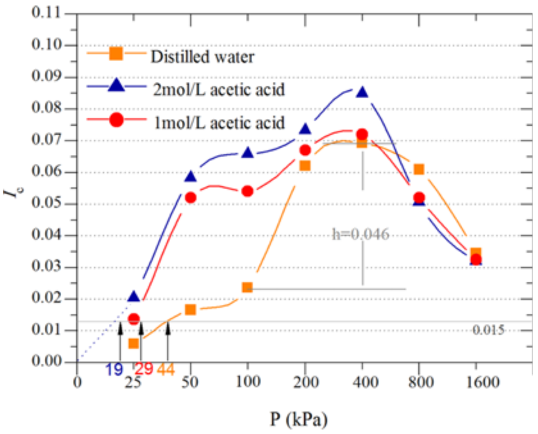

Fig. 6. Relationship between the I_c and Vertical Pressure in Different Reagents

osmotic flow and diffusion of acid into the soil (Thyagaraj and Das, 2017). Next, the salts in the soil that provide cementation gradually dissolve in the inundating fluid, and the matrix suction also rapidly decreases (Sivakumar and Wheeler, 2000; Zhang *et al.*, 2017); as a result, the strength of the loess decreases and is not able to sustain the upper load, eventually resulting in collapse (Munoz-Castelblanco *et al*., 2011; Haeri *et al*., 2014; Mihalache and Buscarnera, 2015). This structural damage causes soil particles to slip into the void space and thoroughly compresses the soil sample. As the pressure increases, the connections between soil particles are easily broken after flooding; consequently, the soil sample is easily compressed. However, the situation is entirely different under a higher additional pressure. When the pressure exceeds 400 kPa, rigid connections (including between soil calcium carbonate and other cementations formed by insoluble salts) cannot bear this level of load, causing the soil sample to suffer more serious structural damage before flooding. Hence, the soils are more fully compressed, and, consequently, the collapse decreases after flooding. This inference is also supported by Fig. 3. Under conditions of 50, 200, and 800 kPa, the samples clearly showed that the void space become much smaller and less frequent and the loess evidently became close-grained as the upper load increased before flooding. This result is also consistent with the results of other studies. Jiang *et al.* (2012) and Thyagaraj and Das (2017) reported that wetting-induced deformation is very small when the vertical pressure is less than the structural yield stress of Saturated Soil (SDS), but increases rapidly once the vertical pressure exceeds SDS and then decreases after it reaches the peak value at the structural yield stress of unsaturated soil (GSDS).

4.2 Comparison of the I_c in Acetic Acid Solutions

Figure 6 shows the I_c of samples in different reagents. When the acetic acid concentration is 1 mol/L or 2 mol/L, the I_c has a similar response to that of distilled water, i.e., it increases from 25 kPa to 400 kPa and then decreases from 400 kPa to 1600 kPa. However, before 400 kPa, the I_c of samples in acidic solutions increases substantially compared to that of samples in distilled water. Subsequently, at a load of 800 kPa, the I_c of samples in distilled water is larger than that of the other two samples. At a load of 1600 kPa, the I_c of the three samples are almost the same. Overall, the acidic solution does not exhibit any significant difference from 800 kPa to 1600 kPa. Thus, it is concluded that under a relative low overlying load at 25-400 kPa, the osmotic consolidation, caused by the inundation with different acetic acid solutions, can contribute to the greater collapse (Thyagaraj and Das, 2017). When the inundating fluid flows into the soils, calcium carbonate cement that does not suffer serious damage before flooding can be dissolved more easily by acetic acid, leading to a drastic collapse. By contrast, when the vertical load is from 800 kPa to 1600 kPa, which is beyond the yield stress of the soil (Jiang *et al.*, 2012; Thyagaraj and Das, 2017), calcium carbonate cementation is damaged thoroughly before soaking, and the soil samples are fully compressed under these level loads. However, the water content of these soils is not changed before flooding, and matrix suction is still present. The quick disappearance of suction after immersion is the main factor of collapse after flooding (Sivakumar and Wheeler, 2000; Vilar and Rodrigues, 2011; Casini, 2012; Mihalache and Buscarnera, 2015), which is the reason that the advantage of acetic acid is not obvious when the loads are heavy. This view is supported by Fig. 3 and Fig. 7. From Fig. 3, compared with samples treated with distilled water, the large void space of samples treated with 2 mol/L acetic acid almost disappears under 50 kPa pressure and that with 1 mol/L acetic acid decreases substantially. Samples at 800 kPa in three reagents are all compressed well. The images in Fig. 7 indicate that under a load of 50 kPa, there are quantities of macropores in the samples treated with distilled water, and the diameter of the void space is approximately 60 μm, whereas that in the samples treated by 2 mol/L acetic acid is only 10 μm. Under a load of 200 kPa, the macropores of samples treated with distilled water is evidently reduced, and that treated by of 2 mol/L acetic acid disappears completely. Under a load of 800 kPa, the large void spaces of these two types of samples all disappear. This phenomenon proves that insoluble salts, such as calcium carbonate cementation, have a certain strength and that the upper collapsible loess at ground level cannot be damaged and pressured because of their low self-weight (it is usually believed, based on engineering experience, that the collapsibility of the 6 m upper layer cannot be completely eliminated using the conventional presoaking method) (Vilar and Rodrigues, 2011); however, they can be dissolved by water and acid. This conclusion indicates that the residual collapsible loess treated with an acetic acid solution must be thinner than that treated with water, and the cost on the residual loess must be less. As a result, the acid-addition pre-soaking method can facilitate the construction of the upper part of the collapsible soil and may reduce the total project costs.

4.3 Comparison of the Saturation Deformation

The double- or multiple- collapse phenomenon refers to a loess

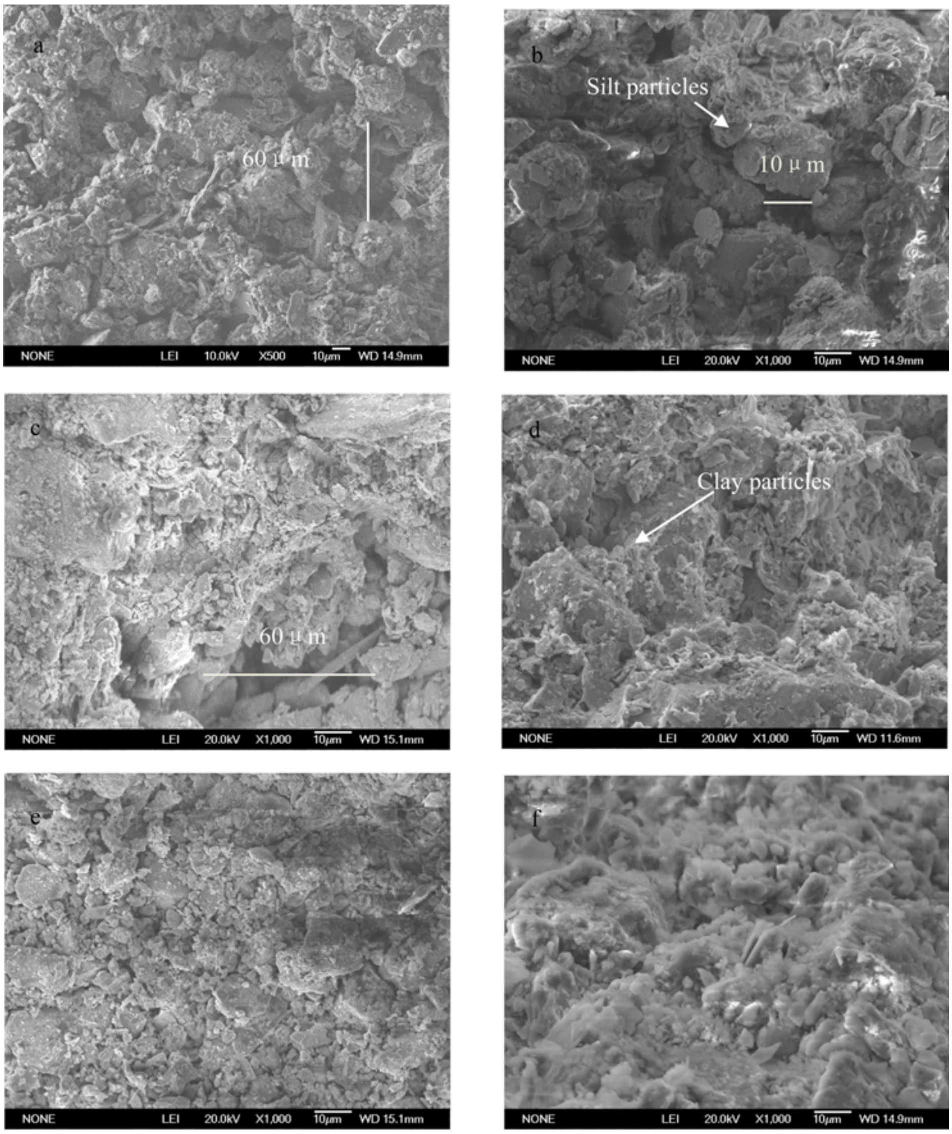

Fig. 7. SEM Images (magnified 1000 ×) of Samples under Conditions of: (a) Distilled Water and 50 kpa Pressure, (b) 2 mol/L Acetic Acid and 50 kpa Pressure, (c) Distilled Water and 200 kpa Pressure, (d) 2 mol/L Acetic Acid and 200 kpa Pressure, (e) Distilled Water and 800 kpa Pressure, (f) 2 mol/L Acetic Acid and 800 kpa Pressure

collapse occurring more than once when the humidity or the overburden pressure of loess is increased (Sun and Liu, 2000). The cause of this phenomenon is that the weight of the shallow upper soil is so slight that Hydro-Mechanical (HM) coupling fails to completely eliminate the collapsibility of the upper loess. As shown in Fig. 6, the I_c of distilled water is approximately 0.024 under a load of 100 kPa and is approximately 0.07 under a load of 400 kPa. The difference is approximately a 0.046, i.e., there is 0.046 potential collapsibility of loess that cannot be released under low pressure. If the pressure is increased under the same saturation condition, then a collapse can occur again. In reality, such a phenomenon occurs when a building is constructed on the ground, as collapse always occurs again because of the increased overburden and rain, even although the ground had previously collapsed.

To investigate the double or multiple collapsibility of loess treated by the acid-addition pre-soaking method, the increased pressure deformation after saturation (saturation deformation) at low loads of 50, 100 and 200 kPa with different concentrations of reagents were investigated, as shown in Fig. 8. When collapse initiates under the initial loads of 50, 100 and 200 kPa, the I_c is in order of 2 mol/L acetic acid > 1 mol/L acetic acid > distilled water. However, when these saturated soil samples are pressurized under more loads as predefined, the saturation deformation result is in order of distilled water > 1 mol/L acetic acid > 2 mol/L acetic acid. The main reason for this result is that, compared to soil samples immersed in distilled water, soil samples immersed in acetic acid are more fully compressed because the cementation connections and void structure are destroyed more severely because of the effect of HM coupling and acetic acid "catalysis".

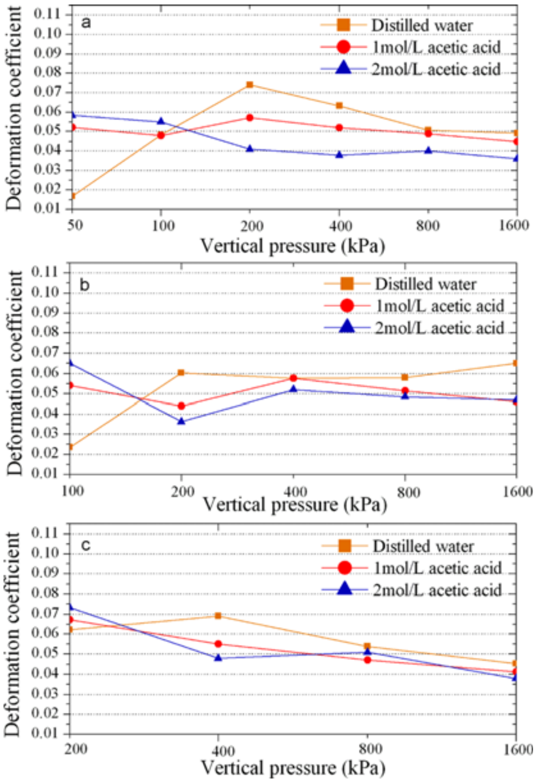

Fig. 8. Comparison of Saturation Deformation after in Different Reagents after Application of Pressures of: (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

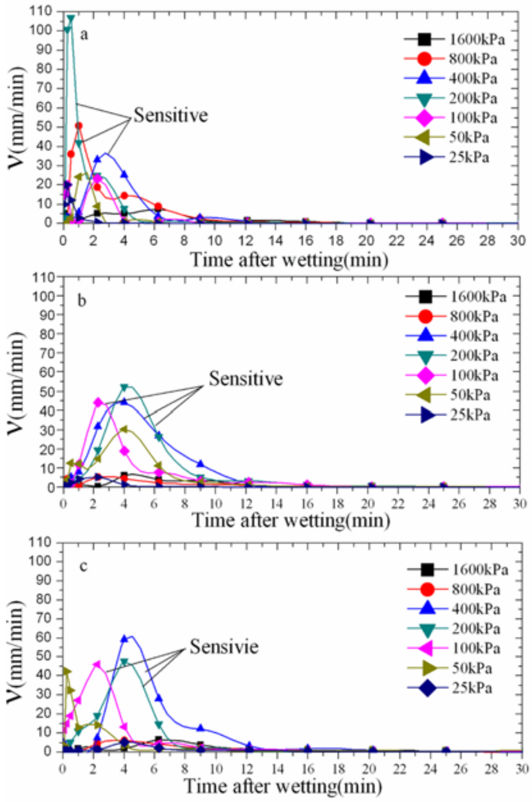

Fig. 9. Relationship under Different Vertical Pressures between the Collapsible Deformation Rate and Time in: (a) Distilled Water, (b) 1 mol/L Acetic Acidm, (c) 2 mol/L Acetic Acid

Thus, the loess saturation deformation significantly decreases when the saturated loess samples are pressurized again. These results prove that, compared with the conventional pre-soaking method, the acid-addition pre-soaking method substantially reduces the risk and harmfulness of multiple or double loess collapse.

4.4 Comparison of the Collapse Rate

The collapse rate, which is the change of the wetting subsidence at different time periods, can be defined by Eq. (3).

$$v = \frac{h_n - h_{(n-1)}}{t_n - t_{(n-1)}} \tag{3}$$

where h_n and $h_{(n\text{-}1)}$ are the wetting subsidence (mm) at the corresponding time points t_n and $t_{(n\text{-}1)}$, respectively.

Figure 9 shows the collapse rate in different reagents under different stresses before 30 minutes. The collapse rates of OW2 and OW1 are high and continue to grow over a period time at 100, 200 and 400 kPa, reflecting greater sensitivity, and OW0 is more sensitive at 200, 400 and 800 kPa. Each reagent has a relatively sensitive pressure section (in other words, each reagent has particularly pronounced effects at pressures within a certain range). Below the pressure section, HM coupling cannot fully compress the soil sample, whereas, above the pressure section, the soil sample is fully compressed before flooding, resulting in less residual spaces, and difficulty in compression during flooding. Fig. 6 shows that the initial collapse pressure of the soil samples decreases from 44 kPa in distilled water to 29 and 19 kPa in acetic acid. The reason for this observation is that many cementation connections are not damaged after being inundated under low pressure. However, with the help of acetic acid, the cementation connections can be quickly destroyed, resulting in the rapid compression of soil samples under low pressure, which indicates that the sensitivity of loss in acetic acid is increased under a low load. Thus, compared to the ordinary pre-soaking method using the saturation weight pressure to eliminate the collapsibility of self-weight collapsible loess, the acid-addition pre-soaking method, with the help of acetic acid, can be applied to a non-self-weight collapsible loess as it reduces the pressure requirements of collapse and makes a non-self-weight collapsible loess collapse under lower pressure.

4.5 Comparison of the Stability Time of Collapse and Stability Time of Saturation Deformation

Figure 10 shows the stability time in different reagents at different vertical pressures. In the collapsible tests, the stability time of distilled water is the longest, followed by that of 1 mol/L acetic acid and 2 mol/L. After wetting immersion, a certain amount of time is required for soil to react with the acid to dissolve calcium carbonate and other insoluble salts. The higher the concentration of acetic acid, the longer the reaction time. In

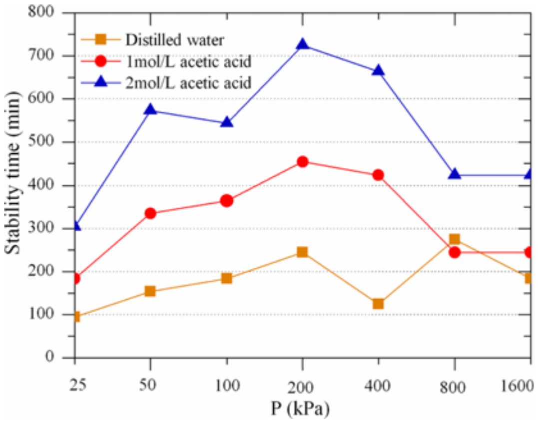

Fig. 10. Relationship between the Stability Time and Vertical Pressure in Different Reagents

this process, calcium carbonate gradually dissolves, and the colloidal connection strength also gradually weakens. The soil samples are slowly compressed under the unchanged upper pressure until the reaction of acetic acid and calcium carbonate tends to be stable and the upper load cannot cause the soil samples to change remarkably.

Figure 11 presents the stability time of the saturation deformation. When the different reagents are injected initially, the stability time of collapse is in the order of 2 mol/L acetic acid > 1 mol/L acetic acid > distilled water. However, one day later, when greater pressure is applied for saturation deformation, the stability time of 2 mol/L acetic acid is obviously less than that of distilled water because after approximately one day of a sufficient reaction time, the majority of soil cement connections are decomposed. When more pressure is applied again, the soil samples require only a short period to complete saturation deformation. In samples in distilled water, more connections exist that can be destroyed; as a result, these samples require more time to complete saturation deformation. Thus, the acid-addition pre-soaking method in outdoor locations should achieve stability faster than the conventional pre-soaking method because of the adequate reaction time (the construction period of the pre-soaking method is always greater than 3 months). The acid-addition pre-soaking method can significantly reduce the construction time, thereby addressing a weakness of the conventional pre-soaking method. Moreover, the proposed method can save water resources and reduce working time, thereby reducing the cost.

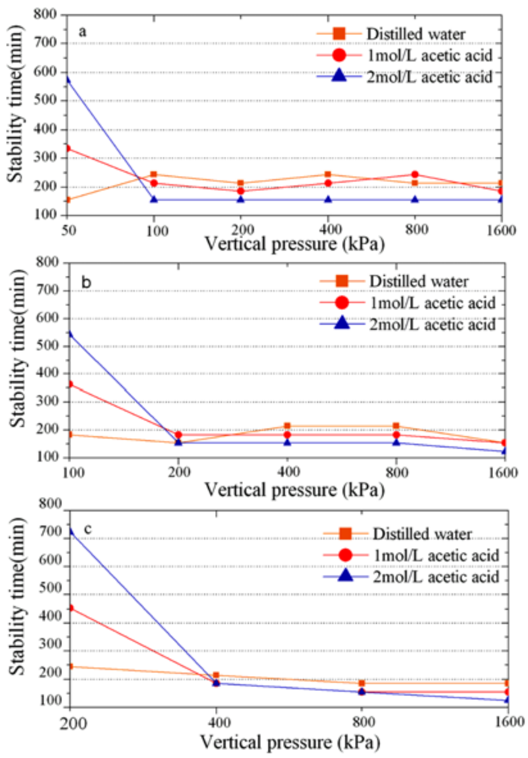

Fig. 11. Comparison of the Stability Time of Saturation Deformation in Different Reagents after Application of Pressures of: (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

4.6 Comparison of the Mechanical Properties

As the mechanical properties of soils are vitally important for construction (Sun *et al*., 2015), consolidated quick shear tests on samples exposed to different reagents are performed to explore the shear strength of soils treated with different acetic acid solutions. The shear strength is defined as follows:

$$\tau_f = c + \sigma tg\phi \tag{4}$$

where τf is the shear stress on the failure surface, i.e., the shear strength of the soil (kPa); c is the cohesion of the soil (kPa); σ is the vertical pressure on the failure surface (kPa); and ϕ is the internal friction angle of the soil (^{0}).

Figure 12 shows the strength envelopes of the shear tests. The test results of distilled water are consistent with the those of Wheeler and Sivakumar (2000). As the soil of CO0 is immersed in distilled water, the cohesion is decreased to a value below 0, which is considered to be 0 in this paper. The strength envelope, which is fitted from the data of CQ2, is above those of CO0 and CQ1, whereas that of CQ0 is the lowest. Eq. (4) shows that the shear strength of soil is determined by the cohesion and the internal friction angle of soil under the same vertical pressure. As shown in Fig. 12, the enhancement of shear strength is mainly caused by the improvement of the cohesion strength, which is increased from 0 to 3.7 and 4.5, and the internal friction angle

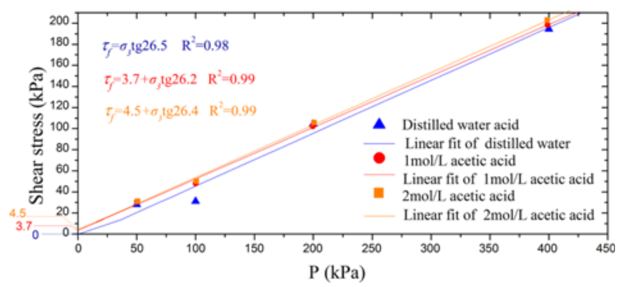

Fig. 12. Relationship between the CQ Strength and Vertical Pressure in Different Reagents

remains almost unchanged, i.e., 26.5°, 26.2° and 26.4°. The cohesion of soil can be divided into the original cohesion force and curing cohesion force (Chen *et al*., 1992). The original cohesion force is derived from the static electricity and the Van der Waals force between particles. Therefore, for the same type of soil, the greater the density, the greater the original cohesion force. Both Fig. 3 and Fig. 7 show that the void spaces of soil treated with acetic acid are much smaller and fewer in number and their densities are higher (as previous analysis). As acetic acid interacts with soluble salts in soil samples, slightly soluble salts and some insoluble salts that are close to the dissolved state are dissolved rapidly, thereby destroying the connections. In the same situation, i.e., under the same vertical pressure, these soil samples are more easily compressed compared to soils treated by distilled water, resulting in a smaller void ratio, higher density and higher original cohesion force. Moreover, the curing cohesion force depends on the strength of the cementing material in the particles. Fig. 7 shows that when flooding in acid solutions occurs, many contact connections are changed into cementation connections and clay particles, which have an excellent cohesive strength, are greater in number than when flooding in distilled water. Thus, the curing cohesion force, total cohesion and shear strength all increase. The more compression the soil undergoes, the higher the density of the soil becomes and the better mechanical quality the soil has. As a result, the mechanical quality of soil treated with using the acid-addition pre-soaking method is better than that treated using the traditional pre-soaking method under a low load because it has a higher density and better structure type.

5. Conclusions

According to the tests results and analysis mentioned above, the characteristics of the collapsibility of loess and improvement effect of the acid-addition pre-soaking method were clarified. The main conclusions of the current paper are as follows:

1. The proposed method has the advantages of flexibility and practicability. In the initial stages of the construction in a field, soils should be sampled in situ to test the contents of soluble salts. Next, the type and amount of added acid are determined according to the amount of soluble salt in soil, thickness of the collapsible loess, quality standards of ground water and soils from different countries.
2. Analyses of the collapsible deformation rate, stability reaction time and I_c shows that collapsible loess is more sensitive when immersed in an acetic acid solution. In particular, under low pressure, the I_c of samples immersed in an acidic solution is much larger than that of samples immersed in distilled water. Under high pressure, the I_c of samples immersed in the three types of reagents does not change significantly.
3. The I_c and subsidence rate of the soil samples show that for the same type of collapsible loess, there is a sensitive section in distilled water, and the sensitivity is enhanced in acid solution, leading to a decrease in the required overburden pressure. Therefore, there is less upper residual collapsible loess after the acid-addition pre-soaking method than after the conventional pre-soaking method, and this method can be applied to non-self-weight collapsible loess.
4. Compared to soil samples immersed in distilled water, soil samples immersed in acetic acid are more fully compressed as the cementation connections and void structure are destroyed more severely by acid. Therefore, the remaining compression space of the soil is much smaller and more difficult to compress again. Thus, the acid-addition pre-soaking method can decrease the risk and harmfulness of multi-collapse of loess.
5. The acid solution can completely and effortlessly dissolve the cementation connections of loess formed by soluble salts, enabling the macropores structure of loess to be quickly destroyed and restructured. Therefore, compared with the conventional pre-soaking method, the acid-addition pre-soaking method can attain stability more quickly, thereby saving water resources and reducing the working time, which may reduce the construction cost.
6. For better compression of loess under low pressure, the cohesion of loess is improved. Thus, the shear strength of loess treated by the acid-addition pre-soaking method is higher than that of loess treated by the conventional pre-soaking method, i.e., the acid-addition pre-soaking method enables soil to have improved mechanical properties.

In conclusion, compared to the conventional method, the acid-addition pre-soaking method can save time and improve the quality of construction. Moreover, the proposed method can be applied to non-self-weight collapsible loess, to which the conventional pre-soaking method cannot be applied. As this is the first study of this proposed method, many further studies of this method should be conducted. For example, besides loess, soft sensitive soil, loose saturated and unsaturated sand, which are widely distributed worldwide, also exhibit collapsibility during wetting (Rao and Revanasiddappa, 2002); thus, further research is required to investigate how the proposed method can be applied in these soils.

Acknowledgements

Many people have contributed to the study of the acid-addition pre-soaking method. Zhu JiWei, Li Yi, Xue ZhiJia, Liu FengYin and Chalwe Lengwe are acknowledged for their great help in revising the manuscript, both technically and editorially. This study was in particular supported by the science and technology innovation project of the Key Laboratory of Shaanxi Province China (2014SZS15-Z02) and the Key Laboratory Foundation of the Ministry of Water Resources of China (YK916006).

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