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Centrifuge model study on settlement of strip footing subject to rising water table in loess

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ABSTRACT

Owing to manmade activities and natural conditions, the groundwater table experiences considerable changes in Lanzhou. Centrifugal model tests were performed to investigate the settlement of strip footings on loess subject to rising water table under different foundation pressures. The air-fall method was employed to reconstitute the artificial loess samples. The applicability of the air-fall prepared samples was evaluated against the parameters of the undisturbed loess samples obtained from the same location. The results of centrifuge tests reveal that the footing settlement increases significantly with increasing foundation loading pressure or increasing rising water table. However, the rate of increase in ultimate footing settlement under combined rising water level and footing pressure is established to be more intriguing.

A simplified method for predicting the ultimate footing settlement on collapsible loess due to rising water table height is proposed. The proposed formulation is verified as there is a good agreement between the test results under various loading pressures and rising water heights and the predicted ultimate footing settlements. A discussion on the ultimate settlement of strip footings subjected to rising water table against conventional bearing capacity safety factors is presented to provide some basis for the foundation design consideration under rising water scenario.

**Key words**: Loess deformation and collapsibility; Rising water table; Footing; Centrifuge test, Prediction method.
INTRODUCTION

Loess soils, known to shrink severely upon wetting, can be found in many parts of the world (Pecsi 1990). The collapse of loess under the combined effects of wetting and loading is termed the process of hydro-consolidation. Owing to its large void structure, the wetting of loess would lead to a significant volumetric decrease. Such wetting collapse deformation is a major geotechnical problem in loess areas and results in excessive foundation deformation and instability (Renéjacques 1988; Sweeney and Smalley 1988; Tan 1988; Rogers et al. 1995; Gao et al. 1996; Houston et al. 1988; Delage et al. 2005; Derbyshire 2011).

It is reported that the change in groundwater table in loess soils may be caused by global warming, concentrated rainfall, earthquakes, urbanization, irrigation, or the construction of hydropower station and other large water conservancy projects (Rogers et al. 1994; Vilar 2011; Zhu et al. 2014; Lv et al. 2014; Sun and Zhong 2015). Rising groundwater table is established to be an important factor causing severe deformation of loess (Krutov 1987; El Nimr et al. 1995).

Lanzhou, with the Yellow River flowing through the city, is located within the collapsible loess soil region in the northwestern part of China, see Fig. 1. Owing to manmade or natural activities, the groundwater table has experienced considerable changes in Lanzhou and the surrounding areas. Zhang (2013) reported that after the construction of a reservoir and subsequent agriculture drainage activities on the Heifengtai plateau in the southwest suburb of Lanzhou, the underground water has risen by 20m and the plateau has subsided by about 5.9m. Wen et al. (2015) reported that 86% of the buildings in Heifengtai encountered excessive settlements and cracks in the walls. Zeng and Zhou (2016) reported that for the urban area of Lanzhou, the
The groundwater table has risen by 10m due to urbanization since 1950s, resulting in more than 40% of the underground civil air defense facilities being flooded. After a heavy rainfall in Lanzhou, Sun and Zhong (2015) reported that the groundwater table has risen by at least 2.5m. This results in massive subsidence of loess in Lanzhou with reported severe damages to existing buildings and structures. Fig. 2 illustrates the damage of houses due to rising water table in Lanzhou.

In view of the above, it is important to evaluate the deformation and collapsibility of loess for the design, construction and maintenance of buildings in loess areas. In the present study, a series of centrifuge model tests have been performed to investigate the settlement of strip footings subjected to rising water table under different foundation loading pressures. The test results are presented and interpreted in detail in this paper.

**REVIEW OF EXISTING STUDIES**

Basma (1993), Liu et al. (1994), and Ayadat and Hanna (2007) studied the effect of macroscopic physical properties of loess including water content, initial dry unit weight, grain size and porosity on the settlement of loess. On the other hand, Feda (1988), Klukanova and Sajgalik (1994) and Muxart et al. (1995) investigated the effect of micro structures, the changes in fabric during inundation and chemical component on the collapsibility mechanism of loess. Sun et al. (2007) investigated the collapse behavior of unsaturated compacted soil having different initial soil densities using controlled-suction triaxial tests. Haeri et al. (2016) conducted wetting-induced collapse and suction-controlled triaxial tests to characterize the role of specimen disturbance and structure on the hydromechanical behavior of collapsible soils. The thermal effect on yield and wetting-induced collapse of recompacted and intact loess was studied by Ng et al. (2018) using a suction- and temperature-controlled double cell triaxial apparatus.
Several ground improvement methods were suggested to reduce the wetting-induced collapse settlement. Souza et al. (1995) employed plate load tests to investigate the applicability of the compaction method. Ayadat and Hanna (2005) introduced encapsulated sand columns as an improvement technique for collapsible soils. Jefferson et al. (2008) proposed to use cement to reinforce collapsible loess. Hanna and Soliman (2017) presented a design method for rigid strip footings on homogeneous collapsible soils, partially replaced collapsible soils with cohesionless material with and without geotextile layer placed at the interface.

With the capability of simulating high geo-stress, relative low cost and data reliability, centrifuge model studies have been employed to investigate problems related to loess. Zhang et al. (1998) conducted a series of centrifuge tests to investigate the optimum compaction density in loess embankments and its effect on the embankment slope stability. Wang et al. (2014) studied the behavior of excavation in tall loess slopes supported with different reinforcement modes. Mu et al. (2016) investigated the effect of irrigation on the stability of loess slopes. Centrifuge model tests were conducted by Wang et al. (2010) to simulate water immersion in undisturbed loess to investigate the loess settlement and downdrag on pile foundations. Water immersion tests were also conducted on undisturbed collapsible loess of various water contents by Jin et al. (2016) to study the effects of degree of saturation and self-weight on loess deformation. Their results revealed that the deformation of loess under self-weight depends on the degree of saturation and the thickness of loess soil. They proposed a hyperbolic paraboloid function in 3-dimensional space involving self-weight deformation, thickness of loess and degree of soil saturation. Qiu et al. (2017) conducted centrifuge model tests to study the ground surface settlement due to twin-tunneling in loess strata. As far as the authors
are aware, there is no report of centrifuge model study on the evaluation of rising water table in loess on the settlement of shallow foundations resting on loess.

SAMPLE PREPARATION FOR CENTRIFUGE TESTS

Existing preparation methods

Several reported centrifuge studies employed undisturbed collapsible soil samples (Wang et al. 2010; Jin et al. 2016; Mu et al. 2016), while others used remoulded soil samples (Zhang et al. 1998; Wang et al. 2014; Qiu et al. 2017; Ng et al. 2016). During the sampling and transport of the undisturbed samples, vibrations and evaporation are inevitable and this may result in damaging the loess structure and a change in its water content. In addition, it may be hard to ensure uniformity among samples in different tests due to the presence of shells, roots and dead insects in the undisturbed samples. As a result, Wang et al. (2010) reported that centrifuge tests employing undisturbed loess typically show wide scatter in test results due to inconsistent soil samples. For the preparation of remoulded samples, the compaction method is one of the most commonly used methods, which can control the water content, density, and void ratio of samples. To create collapsible samples, Pereira and Fredlund (2000) reported that the compaction curve obtained using AASHTO’s standard energy test is needed to determine the appropriate water content and dry density. However, the natural water content of Lanzhou loess is very low (<5%). Such compaction curve is difficult to obtain for very dry loess soil. In addition, it is also hard to control the uniformity of very dry samples using compaction.

Loess is a widespread superficial aeolian deposit, of which the open structure consists of an open skeleton of particles, bonded by various clay and carbonate bridges and skins. It is widely accepted that the airfall aspect of the sedimentation process is essentially responsible for the open structure that collapses when loaded and wetted...
(Assallay et al. 1997; Liu et al. 2016). In view that loess is a classic airfall deposit, Assallay et al. (1997) proposed an airfall method to simulate the natural sedimentation process to reconstitute the open structure of loess.

**Sample preparation method**

In the present study, the air-fall method proposed by Assallay et al. (1997) is employed to prepare reconstituted loess samples to simulate the natural aeolian disposition of loess. Oedometer tests were conducted to verify if the method can indeed prepare appropriate reconstituted loess samples suitable for the study of wetting deformation of loess. By comparing the characteristics of the reconstituted samples with those of undisturbed samples collected at the same location, it can be established that whether the remolded samples can reconstitute the open soil structure of loess or not.

**Properties of undisturbed loess**

To ensure purity of samples, the loess soil in the present study was collected at 0.37m depth at Jinchuan Science Park of Lanzhou. For collapsible soils, Feng (2009) reported that the dry density would typically range from 1.14 to 1.69g/cm$^3$, the void ratio would range from 0.85 to 1.24, the plastic limit would range from 14% to 21%, the liquid limit would range from 20% to 35%, and the plasticity index would fall within a general range of 9 to 12. The physical and mechanical properties of the undisturbed loess given in Table 1 illustrate that the loess properties conform to the characteristics of collapsible soil. The particle size distribution curve of the undisturbed loess is shown in Fig. 3.

**Sample preparation of undisturbed and artificial air-fall loess for oedometer test**

The procedure given in British Standards 1377 (British Standards Institution, 1990) for the preparation of undisturbed samples for standard oedometer tests is adopted in
the present study. Firstly, a 50mm diameter and 19mm deep oedometer specimen was carefully trimmed from a sealed sample collected from the field. The specimen was then placed within a rigid confinement ring and loaded progressively under a vertical pressure ranging from 5 kPa to 400 kPa, which simulated overburden pressure of prototype soil depth ranging from 0.37m to 30m in the subsequent centrifuge tests. The volume change of the sample was recorded by monitoring the vertical displacement of the rigid top cap.

For the reconstitution of a collapsible soil, Rogers and Smalley (1993) demonstrated that particle sizes ranging from 10μm to 60μm are the most suitable to model its structure and packing. To achieve the above, the present setup of oedometer included a 63-micron sieve, an oedometer ring resting on filter paper and porous stone disc, see Fig. 4. The material used to create the artificial samples was pulverized from the same natural undisturbed loess from the Jinchuan Science Park site. Fig. 3 shows that the particle size distribution of the artificial and undisturbed samples are reasonably close to each other.

To ensure a uniform distribution of particles, the loess particles were introduced into the sieve and allowed to free fall into the oedometer by gently shaking the sieve. As the size of loess particles is very small such that the effects of gravity are not great, the air resistance to the falling particles would govern the soil settling speed. Assallay et al. (1997) established that a fall height of at least 250mm is sufficient to achieve the terminal velocity of the particles. As such, the sieve was placed at a constant height of 250 mm above the soil surface to simulate the settling action of aeolian dust particles taking up random positioning over the sample mould. After the mould was filled, the surface was levelled off. The dry density was determined to be 1.01g/cm³ with a very
high void ratio of 1.68. At this point, the sample structure was wide open and sensitive to vibration. The initial unstable structure would not be able to support any load.

To tackle the unstable assembly and to reduce the giant pores of the sample structure, Assallay et al. (1997) suggested the application of a small loading to simulate the vertical stress of overlying material to achieve a "metastable structure". As the soil sample was collected at a depth of 0.37m (equivalent to an overburden pressure of 5 kPa), the top cap was then put on the sample to apply a vertical pressure of 5 kPa. This process was repeated by adding more loess particles and then subject to a vertical pressure of 5 kPa to achieve a uniform sample. During this stage, the unstable particles partially collapsed into the giant pores larger than the particles size. The final soil sample had a void ratio of 1.10 and a dry density of 1.29 g/cm$^3$, the same as those of undisturbed sample. The sample was then transferred to the oedometer test rig ready to be tested.

**Test results**

A shallow foundation would settle under loading due to compressibility of the soil beneath the foundation. In the case of loess, the settlement or collapsibility due to intrusion of water is also a major concern. To assess the suitability of the sample preparation method, the collapse potential and hydro-consolidation behaviour between the artificial and undisturbed samples are compared next.

**Collapse potential**

Collapse potential ($I_c$), which can be measured from oedometer tests, is a key parameter to evaluate the collapsibility of loess. A larger collapse potential leads to a larger wetting collapse deformation of loess and potentially causes greater damage to
the buildings and foundation resting on loess. Following ASTM D5333-03 (2003), $I_c$ is defined as

$$I_c = \frac{\Delta H}{H_0} = \frac{e_1 - e_2}{1 + e_0}$$

where $H_0$ is the original sample height just before inundation; $\Delta H$ is the change in sample height due to inundation; $e_0$ is the initial void ratio; $e_1$ is the void ratio under pressure $p$ pre-compressed in water immersion test; and $e_2$ is the void ratio under pressure $p$ post-compressed in water immersion test.

To evaluate the collapse potential of the loess under various pressures, 12 different loading pressures ranging from 25kPa to 400kPa were applied on both artificial and undisturbed loess samples. When the displacement of the top cap stabilized under a loading pressure, the samples were flooded via the top and bottom porous stone discs (see Fig. 5(a)). The wetting-induced ultimate vertical displacement was recorded to determine the collapse potential of artificial and undisturbed loess at different loading pressures.

Fig. 5(b) plots the collapse potential $I_c$ against loading pressure for both types of samples. It is evident that the artificial loess can simulate and replicate the general trend of the wetting collapse deformation of loess. The $I_c$ for both soils increases with the applied pressure before the peak point, and reaches the peak magnitude at the same pressure of 150 kPa. However, the $I_c$ of the artificial loess is about 1.4 times that of the undisturbed loess. After that $I_c$ decreases with increasing pressure.

**Hydro-consolidation behaviour**

In this subsection, two artificial samples were prepared with an aim to obtain the relationship of void ratio $e$ against pressure $p$ under two different scenarios. One sample was kept at the natural water content throughout the experiment and the other was wet
(i.e. fully saturated) throughout the experiment. The wet samples were created by adding water after the displacement of the top cap became stable under the initial vertical stress of 5 kPa. Table 1 reveals that the natural water content of the natural samples was merely 3.5% and such samples can be deemed “dry”. Thus in this paper, “dry” samples refer to those at the natural water content. The samples were then subjected to loading pressure ranging from 5 kPa to 400 kPa and the corresponding void ratio at the end of each loading was measured.

Fig. 6 shows the variation of $e$ versus log $p$ for the two artificial loess samples. For comparison, the corresponding results for undisturbed loess samples are also presented in the figure. For both undisturbed and artificial “dry” samples, Fig. 6 reveals that the intersection of the two lines fitted on the pseudo-elastic and plastic section of the compression curve corresponds to a vertical pressure of about 140 kPa. Following Sridharan et al. (1991), this vertical pressure denotes the initial yield stress. Previous studies (Sun et al. 2007; Munoz-Castelblanco et al. 2011 and Ng et al. 2018) revealed that the peak collapse potential usually takes place at a vertical pressure close to the initial yield stress. This is attributed to the fact that once the vertical pressure is larger than the initial yield stress, the loess open structure begins to degrade, thereby resulting in a reduction in the collapse. Their findings help to explain the phenomenon that the peak point in Fig. 5(b) occurred at a vertical pressure of around 150 kPa.

On the other hand, for both undisturbed and artificial “wet” samples, the reduction in void ratio is significant right from the smallest loading pressure of 5 kPa. In addition, there appears a reasonably close linear relationship between void ratio and log pressure. The reduction in $e$ with increasing $p$ is reasonably consistent between the undisturbed and artificial loess. However, the artificial samples underwent greater deformation with increasing pressure prior to wetting than the undisturbed samples. The reduction in void
ratio of the undisturbed sample was 0.051 while the reduction in the void ratio of the artificial sample was 0.073.

To further compare the compressibility of undisturbed and artificial loess, the coefficient of volume compressibility, \( m_v \), at different loading ranges were calculated. The comparison of \( m_v \) for both dry and wet conditions are shown in Fig. 7. Fig. 7(a) reveals that the difference in \( m_v \) values between undisturbed and artificial soils in the dry state does not exceed 12\% in the extreme case with an average difference of 9\%. Besides, the difference in \( m_v \) between undisturbed and artificial soils in the wet state is significantly smaller being not exceeding 6.5\% for the extreme case with an average difference of merely 4\%, see Fig. 7(b).

The cohesion and the internal friction angle of the dry artificial sample were determined to be 13.2 kPa and 24.4\(^\circ\), respectively, using direct shear tests. Compared with the corresponding \( c \) and \( \phi \) values of the dry undisturbed loess given in Table 1, the artificial loess has a slightly smaller friction angle but considerably smaller cohesion. This is consistent with the finding of Assallay et al. (1997) who reported that the bonding between the particles of the undisturbed loess should be stronger than that of the artificial one due to stress and environmental histories.

The formation of loess is a continuous process during the entire quaternary period till to date. However, the air-fall method could not simulate the effect of stress and environmental histories of natural loess. In addition, the cohesion of the artificial loess is considerably smaller than that of undisturbed loess. As such, the characteristics of loess under load and wetting in the original state may not be strictly reproduced. It is believed that the present artificial loess sample prepared by the air-fall method may better simulate newly deposited loess as the shorter the sedimentary age of the loess, the closer the simulation between the natural and the present artificial loess.
Nonetheless, as the study mainly focuses on investigating the severe settlement of loess soils upon rising water table (i.e. wetting), the similarity of the natural and artificial loess test results under wetting should still be valid to a large extent in the appreciation on the trend of changing settlement with rising water table though the settlement magnitude may not be exact.

CENTRIFUGE MODEL SET UP

The key advantage of geotechnical centrifuge modelling is the ability to simulate the stress and strain behaviour of the prototype (Taylor 1995). The main objectives of the present centrifuge model study are to investigate under the scenario of rising water table, (i) the deformation characteristics of loess under the action of gravity stress; (ii) the deformation characteristics and the extent of influence of a strip footing under loading; and (iii) the verification of the proposed settlement prediction method.

All the tests were carried out at 30g in the National University of Singapore geotechnical centrifuge. Fig. 8 shows the front view, side view, top view and a photograph of the centrifuge model setup. The internal size of the model box containing loess sample is 550 mm long, 252 mm wide and 250 mm high. To reduce the friction between the soil and the container walls, a layer of grease was coated onto the internal wall of the model container. The appropriate quantity of grease applied was determined by trial and error from the preliminary tests ensuring that the experiments replicate a plane strain condition. A water tank was placed behind the model box (Fig. 8(b)) and connected to the water tank actuator via a closed-loop hydraulic servo-valve control system to control the vertical movement of the tank. By raising the water tank, water would flow into the model box through four tubes to simulate the rising water table in-flight. To facilitate an even distribution of water, the tubes were embedded in a 30-mm
thick sand at the base of the model box. A canvas cloth was placed above the sand to prevent any infiltration of sand into the loess soil.

Similar to the oedometer tests mentioned earlier, the airfall method was employed to prepare the loess sample in the centrifuge tests. Loess particles were placed on a 63-micron sieve and allowed to fall freely into the model box under gravity at a constant height of 250 mm above the loess surface. Loess of 6.78 kg in weight was used each time, after which the sample was compressed using a hydraulic press under an initial pressure of 5 kPa. This process was repeated until a total of 27.1 kg of loess has been placed to reach the final height of 152 mm.

After completion of loess placement, the centrifuge was spun up to 30g and the soil sample reached a final height of 150 mm under the centrifugal acceleration, simulating a 4.5-m thick loess in prototype scale. During this process, the model strip footing was held by the footing actuator via a closed-loop hydraulic servo-valve control actuator placed on the top of the model box so as to avoid any contact with the loess.

Zeng and Zhou (2016) reported that the ground water level in Xigu (a district of Lanzhou near the Yellow River) is around 4.5 m below the ground level. As the soil deformation is comparatively negligible for the saturated loess below the water table, only a 4.5-m thick dry loess layer was modelled in the centrifuge tests to investigate the effect of rising water table on the footing settlement. However, it should be noted that in reality, there is a transition ‘partially saturated’ zone between the saturated loess and the dry loess. The thickness of this transition zone is typically very small in Lanzhou and is hence not modelled in the present study. As such, it is expected that the loess settlement obtained from the present tests would be slightly different from that in the field.
The model footing was fabricated from stainless steel by a high-precision numerical controlled machine tool. As the particle sizes of loess are very small (Fig. 3), there are sufficient particles beneath the footing that the prototype footing performance can be reliably simulated. In addition, the given range of particle sizes and loading magnitude also do not affect the footing performance (no early crushing of particles as an example) according to the finding of Bolton and Lau (1988).

To achieve the least disturbance to the top soil, the footing was slowly placed on the loess in-flight using the footing actuator under a desired footing pressure via a closed-loop hydraulic servo-valve control system. The foundation load was monitored by a load cell rigidly connected between the actuator and footing. Such arrangement would ensure the footing to settle vertically without any tilt. The model strip footing was 30 mm wide (0.9 m in prototype scale), 40 mm thick and 250 mm long occupying the entire width of the model container. Such footing is deemed sufficiently rigid with minimal bending upon loading. Ovesen (1979) shows that the container boundary effect is negligible when the distance of the foundation to the container wall is 2.82 times larger than the foundation width. Thus the boundary effect in the present study should be insignificant as the footing is over 8 times its width from the boundary.

After the completion of the soil settlement under the given foundation pressure, the water table rising process was then initiated. Five potentiometers were used to measure the induced soil settlement at various distances from the footing edge, see Fig. 8(c). Owing to relatively large footing actuator, there is limitation of space and only one potentiometer could be placed to monitor the footing settlement. It is believed that such arrangement is adequate to obtain the footing settlement as the footing is rigid and the ground is uniform before the start of test, as will be reported later.
Groundwater flow is deemed a seepage process and assumed to follow Darcy’s law (Ridder et al. 1994). Thus, the velocity of rising water table follows the scaling laws given in Table 2. Lv et al. (2014) reported that during the flood season of the Yellow river, the maximum velocity of the rising water table in Lanzhou could reach 0.08 m/day. The corresponding velocity in model scale is 1.67 mm/min, which was controlled by the closed-loop servo-valve control system connecting to the water tank via the feedback signal of a pore pressure transducer placed in the tube at the corner of the model box, see Fig. 8(c). Cheng et al. (2008) revealed that the velocity of rising water table would influence the rate of increase in loess settlement but would not affect its ultimate settlement. As the present study mainly focuses on the ultimate settlement, only one velocity was considered.

A total of 25 centrifuge tests were conducted, see Table 3. Test UC is the reference test to evaluate the ultimate bearing capacity of the footing without inundation. The remaining 24 tests were conducted to investigate the settlement of a strip footing on loess subject to rising water table. Tests 1 to 6 are the tests conducted without a footing (i.e. footing pressure $p_f = 0$) under 6 different rising water table heights, $\Delta H$, ranging from 0.9 m to 4.5 m. Tests 7 to 24 were conducted with 3 different footing pressures $p_f$ of 50 kPa, 100 kPa and 200 kPa under the same series of $\Delta H$.

CENTRIFUGE TEST RESULTS

Unless otherwise stated, all the centrifuge test results are presented in prototype scale hereinafter. Fig. 9 presents the load-settlement response from the reference Test UC on footing without inundation. The settlement in the figure refers to the final stable settlement of the footing under the given loading. The ultimate bearing capacity of 320 kPa is determined from the intersection of the tangents of the initial and final load-settlement response.
As cohesion $c$ of 13.2 kPa and friction angle $\phi$ of 24.4$^\circ$ have been determined for the dry artificial loess, the bearing capacity is established to be 303 kPa for the prototype smooth footing and 350 kPa for the prototype rough footing employing the theory of Bolton and Lau (1993). As the measured bearing capacity is 320 kPa (Fig. 9), this reveals that the footing behaves close to a smooth footing.

For the tests without footing (Tests 1-6), the 6 potentiometers (Fig. 8(c)) recorded very similar ground surface settlements illustrating that the loess soil sample in the model container is indeed uniform and consistent. Fig. 10(a) shows the development of green field loess settlement with time under different rising water heights. As rising water table would gradually increase the degree of saturation of the soil, Alonso et al. (1990) reported that the soil suction would gradually reduce to zero. This would weaken the bond among loess particles resulting in a significant reduction in the loess strength. The open structure system of the loess would gradually lose its stability, thereby resulting in severe loess settlement. It is evident that a higher rise in water table would result in more collapse of the loess structure leading to a more significant loess settlement. Fig. 10(a) reveals that the ultimate loess settlement is about 20 cm when the rising water height is 4.5 m as compared to that of about 7 cm under a smaller rising water height of 1.5 m. For typical soils without collapse potential, a rise in water table would normally result in a reduction in effective stress and hence the soil would swell. The present test results reveal that the soil actually settled hence verifying that the artificial loess prepared by the air-fall method is able to simulate the metastable open structure that would collapse when wetted.

Figs. 10(b), (c) and (d) present the footing settlement at different loading pressures and rising water heights. It is evident that the ultimate footing settlement increases significantly with increasing footing pressure. This is mainly due to a greater loading
pressure would cause greater shear stresses at the loess particles resulting in further strength weakening of the loess, thereby resulting in a greater foundation settlement. Fig. 10 reveals that for rising water height of 4.5m, the settlement increases from about 20cm without foundation loading, to about 47cm under a footing loading pressure of 50 kPa, to about 70cm under a pressure of 100 kPa and a significant 122cm under the largest footing pressure of 200 kPa.

Fig. 10 also reveals that the settlement kept increasing after water inundation has been completed. Table 3 shows the duration of water inundation for different rising water table heights. The duration ranges from 11 days for 0.9m rising water height to 56 days for 4.5m rising water height. It should be noted that the dissolution of salt is an important factor causing the collapse of loess structure and the redistribution of loess particles to form a new stable structure (Muxart et al. 1995). The compositions and fractions of soluble salts of the loess are listed in Table 4. As the duration of inundation is relatively short, it is believed that the dissolution of the soluble salt inside the soil had not been completed. As such, the time for reaching the final footing settlement may be somewhat affected but it is believed that the magnitude of the final settlement obtained should still be reasonable.

The observed ultimate footing settlement $S_{\text{ult},pf}^{\Delta H}$ against $\Delta H$ for Tests 1 to 24 are summarized in Fig. 11. The superscript $\Delta H$ of ultimate settlement $S_{\text{ult}}$ refers to rising water table height while subscript $p_f$ refers to the loading pressure. As presented earlier, the ultimate settlement increases with increasing rising water level for a footing under the same loading pressure $p_f$. Under the same $\Delta H$, a larger $p_f$ would cause a greater footing settlement. This implies that when a building supported on footings encounters rising water table, the difference in the foundation loading pressures between neighbouring footings could induce a significant differential settlement. Burland and
Wroth (1974) highlighted that excessive differential settlement could result in cracks and structural damage of buildings.

To facilitate further interpretations of the test results, the observed normalized ultimate footing settlements (defined as ultimate settlement under footing pressure \( p_f \) over ultimate green field settlement at the same rising water height) are evaluated. The results are presented in Fig. 12 which reveals the normalized ultimate footing settlement \( \frac{s_{ult,pf}}{s_{ult,0}} \) decreases with increasing rising water table height. This is mainly because the presence of the footing would cause larger additional stress in the loess, thereby for the same rising water table height, a larger proportion of the loess settlement had taken place earlier than that without footing.

Fig. 12 also shows the normalized footing and ground settlement troughs of obtained from Tests 7 to 24. Owing to symmetry, it is only necessary to present one half of the test results from the mid-footing to the right edge of the model box. The first data points on the left-hand side of each figure in Fig. 12 denote the normalized ultimate footing settlement. As expected, the ultimate footing settlement is much larger than the ground settlement outside the footing. The magnitude of ultimate settlement gradually decreases with increasing distance from the footing. This reveals that the footing loading would strongly influence the loess soil adjacent to the foundation with the influence decreases rapidly with increasing distance from the footing. Close to the edge of the model box, the ground surface settlement is very similar to that of the green field (Tests 1 to 6). This further verifies that the container boundary is outside the influence zone of the footing.

In summary, three important key findings of the centrifuge model tests are highlighted as follows:
(a) Under the same footing loading pressure, the ultimate footing settlement increases with increasing rising water table height.

(b) Under the same rising water table, the ultimate footing settlement increases with footing loading pressure.

(c) While the above findings are not unexpected, the footing settlement under a combination of footing loading pressure and rising water table is more intriguing. It is established that if the ultimate footing settlement is normalized by the ultimate green field ground settlement at the same rising water height, the normalized ultimate settlement actually decreases with increasing footing pressure due to earlier occurrence of settlement due to rising water table.

ANALYSIS OF TEST RESULTS

Settlement of footing on fully saturated loess based on collapse potential

As mentioned earlier, the loess above the water table is not entirely dry. Upon water table rising, settlement would occur in this part of loess. The estimation of water content in unsaturated loess is a complicated process. Thus, it is difficult to establish a simple method to evaluate the loess settlement due to rising water table.

However, it is possible to calculate the ultimate settlement of loess under self-weight with the water table rising from the initial level $H$ to the ground surface. Under this special condition, the loess is fully saturated and the calculated results represent the maximum possible green field settlements. In terms of collapse potential given in Eq. (1), the settlement $dS_{ult,0}^H$ of the loess soil layer with a height $dz$ is expressed as

\[ dS_{ult,0}^H = l_C dz \]
Fig. 5(b) shows that $I_C$ is a function of the loading. For the maximum possible green field collapse settlements $S_{ult,0}^{H}$, the load is the sum of the total overburden pressure due to self-weight of the soil $\sigma$, i.e. the total overburden pressure at the given elevation. $S_{ult,0}^{H}$ can then be obtained by integrating Eq. (2) along the depth of loess. In fact, this is also a method recommended by the Chinese Code for building construction in collapsible loess regions, National Standard of China (GB50025-2004), to evaluate the collapse category of loess site.

For the calculation of footing settlement, the additional stress $\Delta q$ at the given location due to foundation loading pressure $p_f$ need to be considered. In addition, it should be noted that the foundation experienced a settlement under the action of the base pressure prior to inundation, such that the loess thickness beneath the footing had a small reduction. By examining the settlement after each loading in Fig. 9, the footing loading pressure of 200 kPa would induce a change of 2% in the thickness of loess layer. If assuming the reduction in the thickness is all converted to the compression of loess void, the maximum variation in loess dry density is no more than 2%. As such, it is sufficiently accurate to adopt the initial loess thickness (before compression) to evaluate the self-weight, the addition stresses and the corresponding collapse potential as the datum of the non-deformed foundation. This would enable the deployment of existing analytical solutions to evaluate the additional stress. As an example, Boussinesq (1969) solved the problem of stresses produced at any point in a 3-dimensional homogeneous and isotropic elastic half space as the result of a point load applied on the surface of the half space. Conventionally, the additional stress $\Delta q$ caused by a strip load of finite width $B$ and infinite length is obtained by integrating the Boussinesq’s stress solution over the strip area. As the soil here is assumed to be a homogeneous and isotropic elastic mass, it has been established that the additional
stress is independent of the elastic modulus of soil. The detailed deduction can be found in Das (1994).

Thus, when considering the additional stress \( \Delta q \) induced by the footing loading pressure, the ultimate footing settlement \( S_{\text{ult, pf}}^H \) with water table rising from the initial level \( H \) to the ground surface can be obtained by integrating Eq. (3) as follow:

\[
S_{\text{ult, pf}}^H = \int_0^H I_C (\sigma + \Delta q) dz = I_C \cdot H
\]

where \( I_C \) is a newly defined average collapse potential of the loess to represent the average collapsibility of a loess layer with footing pressure. Therefore, the green field collapse settlement \( S_{\text{ult, g}}^H \) is a special case of \( S_{\text{ult, pf}}^H \) when the additional stress \( \Delta q \) is taken as zero.

For the present loess soil with finite thickness, Boussinesq’s (1969) elastic half space solution could not capture the distribution of the additional stress along the soil depth. In the present study, the Ai et al. (2002)’s elastic solution is employed to obtain \( \Delta q \), which solves the stresses produced at any point in a 3-dimensional homogeneous and isotropic elastic medium with finite thickness subjected to a point force applied at any point of the medium. The additional stress \( \Delta q \) in an elastic medium with finite thickness induced by a strip load on its surface can also be obtained by integrating the Ai et al. (2002)’s stress solution over the strip area. Conventionally, \( \Delta q \) is written in the form of \( \alpha_c(z,B) \cdot p_f \), where \( \alpha_c(z,B) \) is the additional stress coefficient depending on footing width \( B \) and depth \( z \) below the footing and independent of elastic modulus. The profile of \( \Delta q \) below middle of footing with depth is shown in Fig. 13.

For the soil sample used in the centrifuge tests, the \( I_C \) values are given in Fig. 5. Fig. 14(a) shows a good agreement between the prediction using Eq. 3 and the results from Test 6, Test 12, Test 18, Test 24 for the situation when the rising water table...
reaches the ground surface. The test results reveal that the additional vertical stress induced by the footing loading pressure would induce a fairly large wetting deformation beneath the footing. Fig. 14(b) compares the measured average collapse potential $I_C$ with the calculated ones, whereby a good agreement can be seen. This reveals that the above mentioned assumption is deemed acceptable.

**Effect of rising water table height**

For convenience, $I^g_C$ is defined as the green field average collapse potential ($I_C$ with $p_f=0$). Fig. 15(a) plots the ratio of $\frac{S_{ult,pf}}{S_{ult,0}}$ versus the ratio $\frac{I_c}{I_C^p}$ where $I_C$ and $I_C^p$ are the measured results shown in Fig. 14(b). It can be seen that $\frac{S_{ult,pf}}{S_{ult,0}}$ with $\Delta H = H$ (namely $S^H_{ult,pf}$) increases linearly with $\frac{I_c}{I_C^p}$, as $S^H_{ult, pf} S_{ult, 0}$ is equal to $I_c$ according to the definition of $I_C$ given in Eq. 3. Thus, the ratio $\frac{S_{ult, pf}}{S_{ult, 0}}$ can be further rewritten as follows:

$$\frac{S_{ult, pf}}{S_{ult, 0}} = \frac{S^H_{ult, pf}}{S^H_{ult, 0}} \frac{S^H_{ult, pf}}{S_{ult, 0}} \frac{I_c}{I_C^p}$$

(4)

In addition, it can be observed from Fig. 15(a) that the ratio $\frac{S_{ult, pf}}{S_{ult, 0}}$ for other rising water table heights also increases approximately linearly with $\frac{I_c}{I_C^p}$. The linear fitted lines are also shown in Fig. 15(a) with correlation coefficient $R^2$ of 0.977. This implies that the ratio $\frac{I_c}{I_C^p}$ can be used confidently to represent the effect of various stress distributions in soil caused by the self-weight and footing pressures on the loess settlement by defining the average collapse potential $I_C$ given in Eq. (3). By considering Eq. (4) from a mathematical point of view, the ratio $\frac{S_{ult, pf}}{S_{ult, 0}}$ is the gradient of each fitted line and is an independent factor representing the effect of rising water height on the loess settlement. Thus, the ratio $\frac{S_{ult, pf}}{S_{ult, 0}}$ is defined as the reduction factor $RF_w$, which is introduced to
represent the loess settlement due to rising water height $\Delta H$ in relation to the collapse settlement under the same footing pressure and water table rising to the ground surface.

Fig. 15(b) shows the variation of $RF_w$ versus $\frac{\Delta H}{H}$. The following correlation can be established

$$RF_w = 1 - \left(1 - \frac{\Delta H}{H}\right)^{1.4} \quad (5)$$

The ultimate settlement of a strip footing subjected to rising water table can hence be predicted as follow:

$$S_{ult} = RF_w \cdot S_{ult,pf} = RF_w \cdot I_c \cdot H \quad (6)$$

in which $I_c$, $RF_w$ and $H$ represent the effects of the collapsibility of a loess layer with footing pressure, water rising height and water table depth on the ultimate settlement, respectively. Fig. 16 compares the experimental results and those obtained from the proposed empirical expression given by Eq. (6), where a good agreement can be seen.

As discussed earlier, the artificial sample has a larger collapse potential than the undisturbed sample since the airfall method cannot simulate the effect of deposition history of loess. Thus, the results of the centrifuge tests would be larger than the actual cases. The above effect can be partially tackled by using the empirical expression given by Eq. (6).

**Discussion on design of strip footing subject to rising water table**

Conventional bearing capacity theories or plate load test is commonly employed to determine the ultimate bearing capacity of a strip footing. The allowable foundation loading pressure is then calculated employing a desired safety factor. Depending on the type of structure, a minimum safety factor of 2 to 3 (Feng 2009; Budhu 2012) is necessary to avoid excessive foundation settlement. However, the differential
settlement could play a controlling role in actual projects (Skempton and MacDonald 1956). In practice, the limiting differential settlement is often converted to an allowable settlement in terms of building length or the span between two footings. As such, the maximum allowable settlement will be taken as the limiting value for the ultimate settlement of a strip footing. In the present study, the maximum allowable settlement is taken as 40cm following the National Standard of China (GB50007-2011) for all buildings.

Taking the centrifuge test result as an example, the ultimate bearing capacity of the footing without inundation is 320 kPa (Fig. 9). Taking 2, 2.5 and 3 as the desired safety factors, the allowable bearing pressure is calculated to be 160 kPa, 128 kPa and 107 kPa, respectively. Fig. 17 plots footing settlement versus rising water height obtained by Eq. (6) under the three allowable loading pressures. As expected, a larger safety factor would result in a smaller footing settlement. In other words, a strip footing would withstand a higher rising water table if a larger safety factor has been adopted in the design.

Fig. 17 further illustrates that the footing with a safety factor of 2, 2.5 and 3 is expected to withstand rising water height $\Delta H$ of 1.5m, 1.8m and 2.1m, respectively, with a maximum allowable settlement not exceeding 40cm. As mentioned earlier, the groundwater table height in Lanzhou could rise up to 2.5m, a factor of safety of 3.7 is hence desired. As such, a higher safety factor is recommended for foundation on loess and the desired safety factor for a strip footing would depend on the magnitude of rising groundwater table during the service period of the footing.

If the factor of safety is taken as 3.7, the allowable footing pressure would reduce to 86.5 kPa, which may be not enough to carry the superstructure loads in some cases. Increasing the footing width is a viable option to reduce the applied loading pressure.
However, merely arriving at a footing width such that the loading pressure is within 86.5 kPa may not arrive the feasible solution. One must check whether the ultimate footing settlement is within the desired magnitude (e.g. 40cm) as the induced stresses in the soil beneath and around the footing would be different. When the adjustment of footing width could not satisfy the desired settlement magnitude, the placement of geotextile beneath the foundation may be considered for the design of a footing in collapsible soil, as proposed by Hanna and Soliman (2017).

**CONCLUSIONS**

A series of centrifuge model tests has been carried out to evaluate the effects of rising water table on the settlement of loess foundation in Lanzhou. The airfall method was employed to prepare the artificial loess. The compressibility and collapsibility of the artificial samples is not dissimilar to those of the undisturbed loess though the cohesion of the artificial loess is considerably lower than that of undisturbed loess. As the airfall method could not simulate the stress history of the loess soil structure, the artificial loess is likely to be more suitable for the study of newly deposited loess. For old deposited loess, the observed ultimate settlement magnitude of loess may not be exact but the trend of increasing settlement for various rising water heights and foundation loading pressures should still remain valid.

The centrifuge test results reveal that the ultimate bearing capacity of the present strip foundation without inundation is 320kPa. It is observed that the ultimate footing settlement would increase considerably with increasing rising water height or increasing foundation loading pressure. However, the footing settlement under a combination of footing loading pressure and rising water table is more intriguing. It is established that if the ultimate footing settlement is normalized by the ultimate green
field ground settlement at the same rising water height, the normalized ultimate settlement actually decreases with increasing footing pressure due to earlier occurrence of settlement due to rising water table. The ultimate footing settlement is observed to be much larger than the loess ground settlement outside the footing. The magnitude of loess settlement gradually decreases with increasing distance from the footing revealing a stronger influence on the loess adjacent to the footing.

A simplified method for the prediction of ultimate settlement of a strip footing on saturated loess is proposed based on the combination of additional stress theory and collapse potential. There is a good agreement between the predicted results from Eq. (3) and the test results. Furthermore, the ratio \( \frac{S_{ult,of}}{S_{ult,0}} \) is proposed based on the collapse potential under different pressures and the ratio is found to increase approximately linear with \( \frac{\gamma_c}{\gamma_L} \) with a high correlation coefficient of 0.977. Finally, a formulation of ultimate settlement under various foundation loading pressures and rising water heights is proposed. A good agreement can be seen between the test results and the predicted results. By going through a case of maximum allowable footing settlement of 40cm, it is established that the footings with the factor of safety against bearing capacity failure of 2, 2.5 and 3 could withstand rising water height of 1.5m, 1.8m and 2.1m, respectively. For the case of Lanzhou where the water level could rise by up to 2.5 m, a safety factor against bearing capacity failure of at least 3.7 is found to be necessary for the ultimate footing settlement not exceeding 40cm.
ACKNOWLEDGMENTS

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(Eq. 6)
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Table 1 Properties of the undisturbed loess

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Specific gravity</td>
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<tr>
<td>Plastic limit, %</td>
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<tr>
<td>Liquid limit, %</td>
<td>32.1</td>
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<tr>
<td>Natural moisture content, %</td>
<td>3.5</td>
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<tr>
<td>Void ratio</td>
<td>1.10</td>
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<tr>
<td>Dry density, g/cm³</td>
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<tr>
<td>Cohesion, kPa</td>
<td>34.1 (Undisturbed)</td>
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<td>Internal frictional angle, deg</td>
<td>26.5 (Undisturbed)</td>
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<td></td>
<td>24.4 (Artificial)</td>
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Table 2 Scaling laws for seepage in centrifuge tests

<table>
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<tr>
<th>Parameters</th>
<th>Permeability coefficient</th>
<th>Seepage gradient</th>
<th>Velocity of water table rising</th>
<th>Permeation time</th>
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<td>Unit</td>
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Table 3 Program of centrifuge tests (Prototype scale)

<table>
<thead>
<tr>
<th>Footing pressure p_f (kPa)</th>
<th>Rising water table height, ΔH</th>
<th>Duration of inundation (day)</th>
<th>Soil thickness, H</th>
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<tbody>
<tr>
<td>0 (Without footing)</td>
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<tr>
<td>Test 1</td>
<td>0.9m=B</td>
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<tr>
<td>Test 2</td>
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<tr>
<td>Test 3</td>
<td>2.4m=2.67B</td>
<td>30.00</td>
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<tr>
<td>Test 4</td>
<td>3.0m=3.33B</td>
<td>37.50</td>
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<tr>
<td>Test 5</td>
<td>3.9m=4.33B</td>
<td>48.75</td>
<td>4.5m=5B</td>
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<tr>
<td>Test 6</td>
<td>4.5m=5B</td>
<td>56.25</td>
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<tr>
<td>Test UC</td>
<td>[To evaluate the ultimate capacity of footing natural water content (without inundation)]</td>
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Note: B=width of footing, 0.9m

Table 4 Compositions and fractions of soluble salts

<table>
<thead>
<tr>
<th>Anion content (mg/kg)</th>
<th>Cationic content (mg/kg)</th>
<th>Total soluble salt content (mg/kg)</th>
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<tr>
<td>HCO₃⁻</td>
<td>SO₄²⁻</td>
<td>Cl⁻</td>
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<tr>
<td>170</td>
<td>6358</td>
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