Studies of Deformation Properties of Collapsible Loess Foundation under Overburden Pressure with Large Thickness by Centrifugal Model Test

Songli Jin¹, Yichuan Xing¹, Jun Yan¹*, Weiquan Zhao¹, Shu Zhou²,³, Jianzhang Xiao¹, Shuaifeng Wu¹ and Liming Sun¹

¹State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Department of Geotechnical Engineering, China Institute of Water Resources and Hydro-power Research, Beijing 100048, China
²Key Laboratory of Mountain Hazards and Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
³University of Chinese Academy of Sciences, Beijing 100049, China

*Corresponding author email: yanjunwuhan@163.com

Abstract. At present, laboratory test and field immersion test are the primary methods to study the collapsibility characteristics of loess foundation. However, the stress state of laboratory test usually does not conform to the actual in-site situation, while the field immersion tests are expensive and difficult to operate. Thus, a new economical and efficient method which can reflect the actual engineering is urgently needed. Centrifugal model test, which is the best physical model test, has been extensively used in various fields of geotechnical engineering. However, centrifugal model test is seldom used in the simulation of collapsibility characteristics of loess foundation. In this paper, centrifugal model tests of natural water content foundation and saturated foundation are carried out for the collapsible loess with strong self-weight collapsibility located in Yili Region in Xinjiang, China. The collapsible deformation of loess foundation based on double-line method is obtained. The results show that the amount of foundation collapsibility simulated by low head saturation method is the closest to that of field immersion test, which verifies the feasibility of using centrifugal model test to simulate collapsible deformation of Loess foundation.

Keywords: loess, collapse under overburden pressure, centrifugal model test, field immersion test.

1. Introduction

With the rapid development of economy in China, construction projects in loess regions in Xinjiang Uyghur Autonomous Region (Xinjiang for short) are gradually increasing, and treatment problems of collapsible loess foundation encountered in actual projects in Xinjiang are also increasing. Loess in Xinjiang features its large thickness and significant collapsibility under overburden pressure. However, Code for Building Construction in Collapsible Loess Region [1] (GB 50025-2004) (code 50025 for short)
in China is the only code for collapsible loess in China, in which reference data about loess in Xinjiang is few and of poor applicability. Thus the study of the collapsible characteristics of loess in Xinjiang under overburden pressure is quite necessary.

At present methods for determining the collapse of loess foundation under overburden pressure mainly include field immersion testing method and laboratory testing method. For field immersion testing method the collapse of loess under overburden pressure is measured after soil is saturated in the trial pit excavated in the field. Although realistic data could be obtained by field immersion tests, the cost is high, the water consumption is great and the testing period is long. Besides, in order to reduce the size effect, it is specified in code 50025 that the pit area in the field should be determined based on the thickness of the loess layer. Thus for collapsible loess foundation with large thickness not only the cost is too high, but also the test is often difficult to carry out due to lack of water[2,6]. For laboratory testing method, firstly the coefficient of collapsibility in different depths of loess foundation is measured, then the collapse of loess foundation under overburden pressure is calculated with layered summation method. Laboratory testing method is simple and economical, but the calculated results are usually quite different with the field measured data because of the unloading effect and the difference between the calculated collapsible depth and the actual immersed depth and many other factor[7,8].

Geotechnical centrifugal model test is the best mechanical model testing method by far, and is widely used in high earth-rock dams, underground structures, retaining wall, embankment, slope, soft foundation and many other geotechnical projects [9-14]. The test principle is to simulate the mechanical and deformation characteristics of a prototype of the geotechnical structure under gravity load by increasing the geostatic stress of the model by high-speed centrifuge. Thus, centrifugal model test is suitable for study of the collapsibility of loess under overburden pressure. However, no studies on simulating field immersion test by centrifugal model tests are found in the limited applications of centrifugal model test in loess foundation[14-15].

In this paper, centrifugal model test on loess foundation under gravity stress was conducted combined with the assessment and treatment projects on deep collapsible loess canal foundation in Yili Region in Xinjiang. The feasibility of centrifugal model test simulating field immersion test was demonstrated by comparing the results of centrifugal model test with the measured collapse settlement under overburden pressure. The calculated collapse correction coefficient for Yili Region in Xinjiang was proposed by comparing the measured and calculated collapse settlements under overburden pressure.

2. Physical and mechanical properties of loess

2.1. Sample Situation
In typical locations of the regions applied with the field immersion tests, soil samples at different depths were acquired by excavating pit artificially for all kinds of laboratory tests and the centrifugal model test. Maximum depth of the pit is 30 m and two original loess samples were acquired every one-meter depth of the pit. The size of the original loess samples is about 20 x 20 x 30 cm (h = 30 cm).

2.2. Physical and Mechanical Properties of Loess
According to the result of particles analysis, water content limit test and ring knife test on soil samples of different depths: 1) the soil particle composition changes slightly within a depth of 30 m. The grading curve is distributed in a narrow region, and do not change with the increase of depth. 2) the specific gravity of the soil sample is between 2.70 to 2.73; the plastic limit of moisture content is between 15.3% and 20.6% and the liquid limit of moisture content is between 37.8% and 20.6% and the plasticity index is between 9.8 and 21.9. 3) change of moisture content with depth: The moisture content increases slightly with the increase of the depth within 8 m. When the depth ranges from 8 m to 25 m, the moisture content generally stabilizes around 7%, with an exception at the depth of 11 m. When the depth is more than 25 m, the moisture content is increasing with an average value of about 15%. 4)The change of the dry density with the depth can be divided into two sections. The dry density fluctuates at about 1.24 g/cm$^3$ within 0~13 m, and reaches a minimum value at the depth of 11 m where the maximum moisture
content is found. When the depth is more than 13 m, the dry density increases firstly then decreases, reaching a maximum value of 1.40 g/cm$^3$ at the depth of 18 m while decreasing to 1.24 g/cm$^3$ at depth of 30 m.

It can be seen from the above analysis that the loess in this region within 30 m in thick is relatively uniform. Thus it is appropriate to simulate the stress and deformation characteristics of the loess foundation by geotechnical centrifugal test using the original soil samples.

3. Centrifugal model test

3.1. Experimental Scheme
This experiment was carried out using the 50g·t geotechnical centrifugal testing machine at Tsinghua University. The basic parameters of the centrifugal tests are as follows.

- Effective radius of the turning arm, 2 m (from the loading center to the rotation center).
- The largest centrifugal acceleration is 250 g.
- The net size of the model box used in this experiment is 50 cm x 35 cm x 20 cm. One side of the model box is made of organic glass 5.8 cm thick, and the other three sides and the bottom side are all made of aluminum alloy.

Four centrifugal model tests on the loess foundation under overburden pressure were designed, including three saturated foundation and one foundation of natural moisture content. The three foundations are saturated using pumping gas saturation method, low pressure saturation method, water film transfer saturation method, respectively, with the purpose of analyzing the effects of saturation method on the collapse deformation of the foundation respectively. By calculating the settlement deformations of the foundation with natural moisture content and saturated foundations of the same thickness, the collapse settlement of the foundation under overburden pressure based on double line method was obtained.

3.2. Model Preparation
Preparation of the centrifugal model is as follows.

1) Cut the surface of soil sample smooth keeping natural structure unchanged, then put the sample in the model box along the edge (see Fig. 1).
2) In order to facilitate the compaction, grind the remolded soil (taken from the same trial pit with the original loess sample) and wet it till the water content is close to the optimal water content, and then put it aside sealed for no less than 24 h.
3) Compact the remolded soil layer by layer in the model box till it has the same height with the original loess sample. The dry density of the remolded soil should be kept the same with the original loess sample.
4) Decorate pins with plastic chips as displacement marks on surface A of the soil sample 2 cm spaced to measure the settlement deformation (see Fig. 2).
5) Saturate the foundations using gas saturation method, low pressure saturation method, water film transfer saturation method respectively (for the three saturated models). The initial situation of the models is shown in Table 1.
Table 1. Initial condition of the four models.

| Model name                              | Sample depth[m] | Sample size after cutting[cm] length*width*height | Initial water content [%] | Initial dry density [g/cm³] | Initial wet density [g/cm³] | Specific gravity |
|-----------------------------------------|-----------------|-----------------------------------------------------|---------------------------|------------------------------|-----------------------------|------------------|
| Pumping gas saturation model            | 9.5-10.0        | 18*18*26                                             | 7.23                      | 1.25                         | 1.34                        | 2.71             |
| Low pressure saturation model            | 13.5-14         | 22.5*16.5*27.5                                       | 11.48                     | 1.25                         | 1.39                        | 2.74             |
| Water film transfer saturation model     | 15.5-16         | 20*13.5*27.5                                         | 8.24                      | 1.25                         | 1.35                        | 2.74             |
| Natural moisture content model           | 8.5-9           | 21.5*17.5*26.5                                       | 9                         | 1.25                         | 1.36                        | 2.71             |

3.3. Experimental Methods
Stepping loading method is applied in this tests and the loading step is 10 g. The next level loading will not be applied until the deformation under the current loading level is stable. The stability is judged by the displacement shown in a series of continuous photos. Record the soil displacement under each loading level in the whole process. Due to the instability of the image-acquisition system when running...
at a high acceleration, the actual final acceleration of each model is different. The final acceleration of the low pressure saturation model and water film transfer saturation model is both 100 g. When the acceleration reached 60 g and the deformation was stable, the gas pumping saturation model had to be stopped due to the failure of the image-acquisition system. For the foundation model with natural moisture content, the loading is applied stepwise till 60 g.

3.4. Results and Analysis

3.4.1. Total Settlement of the Model. The analyzing steps are as follows:

1) Select photographs taken at the beginning of the test and at the moment when the deformation was stable at different accelerations.

2) Obtain the vertical coordinates ($Y_j$) of the pins at the top row of the model from these photographs with the software Getdata. The subscript $i$ stand for the pin number and the subscript $j$ stands for the acceleration value. $j = 0$ means no loading is applied at the beginning of the test.

3) By calculating the difference between $Y_j$ of each pin and $Y_{i0}$, the total settlement of the soil unit at the position where the pin is located is obtained under each level of loading.

Results of the total settlement deformation of each model are shown in Fig.3. It can be seen from Fig.3 that the total settlement deformation of each saturated model increases with the increase of centrifugal acceleration. The displacement of the marks in the center of the original soil is selected as the total deformation value of each model (shown in dotted lines in Fig.3).
3.4.2. Collapse Deformation of Loess Foundation. According to the model height and the total settlement of the model under different accelerations, the thickness of the prototype foundation and corresponding total settlement deformation of the foundation are calculated based on the Bockingham’s $\pi$ theorem. Fit the thickness and deformation curves with polynomials, and then the relationship curves between the collapse deformation and foundation thickness can be obtained by subtracting the settlement deformation of the foundation with natural moisture content from the saturated foundation, as shown in Fig. 4. As can be seen from Fig. 4, the collapse deformation of the foundation gradually increases with the foundation thickness. The collapse deformations of different saturated foundations with the same thickness differ significantly. The collapse deformation of the gas pumping saturated foundation is the largest, followed by the low pressure saturated foundation, while the water film transfer saturated foundation is the smallest. This significant difference is mainly caused by different saturating methods. Compared with the water film transfer saturation model, external forces are applied to the soil in the other two models during the saturating process (for gas pumping saturation model negative air pressure is applied and for low pressure saturation model seepage force is applied), leading to greater soil deformation.
In addition, it was found that the three saturated models induced increases in the model height, by measuring the height of the model before and after immersion. The increased value is between 1 cm to 3 cm. The gas pumping saturated model has the greatest increase in height, followed by the low pressure saturated model, while the water film transfer saturated model has the smallest increase. However, it is known that significant collapse deformation will be generated when soaking the foundation in field. These two phenomena seems contrary while in fact not.

The mechanism of the collapsibility of loess is as follows:

Some or all of the soluble salt which plays a role of cementing between the skeleton particles dissolved when encountered with water, thus the coupling effects between the particles are weaken or even destroyed. Then slipping or rearranging of the skeleton particles occurs under certain stress, resulting in the collapse deformation finally. Because the model height is small (25 cm on average), the gravity stress is very small at the acceleration of 1 g, no slipping or rearranging of the skeleton particles can be caused. This phenomenon also proved that the collapse deformation of loess results from the combination of the water pressure and loading. The reason of the increasing height of the model at an acceleration of 1 g is that a lot of fine clay particles are generated in the saturating process which are in suspension in water due to small gravity. They gradually pass through the voids among soil particles, reach the surface of the soil sample and then gather on the surface at a considerable amount, causing the increase of the height of the model.

4. Analysis of the collapsibility of loess under self-weight

4.1. Comparison with the Results of Field Immersion Tests

Accelerated pre-immersing and normal immersing tests were also carried out in the field sampling positions (1# testing pit and 2# testing pit) for centrifugal model test. The diameter of 1# circular testing pit was 30 m, with water injecting holes set in the pit to accelerate immersion. The size of 2# rectangular testing pit is 66 m long and 44 m wide without water injection hole. Results of the field tests show that the immersion depth of 1# testing pit was 30 m and the collapse settlement is 2.7 m, while the immersion depth of 2# testing pit was 16 m and the collapse settlement is 1.2 m.

Substitute two thickness’s (16 m and 30 m) of the foundation into the relationship curves of the three saturated models in Fig. 4, then the collapse deformation of the foundations saturated with different methods is obtained, as shown in Table 2. It can be seen from Table 2 that the results of the centrifugal model tests using low pressure saturation method are very close to the field immersion test results. The relative error of the 16 m thick foundation is 4.7% while the 30 m thick foundation is 10.6%. The above analysis not only indicates the reasonability of using low pressure saturation method to study the
collapse deformation of loess by centrifugal model tests based on double line method, but also demonstrates the feasibility of using centrifugal model tests to simulate field immersion tests.

### Table 2. Foundation collapse with different methods.

| Foundation depth [m] | Centrifugal model testing results | Measured collapse under overburden pressure | Calculated collapse under overburden pressure | Correction coefficient of the measured data, $\beta_0$ |
|----------------------|-----------------------------------|--------------------------------------------|---------------------------------------------|------------------------------------------------ |
| 16                   | Low pressure saturation method    | 1.14                                       | 1.20                                        | 0.95                                           |
|                      | Water film transfer saturation method | 0.71                                       | 2.05                                        | 0.95                                           |
|                      | Pumping gas saturation method     | 2.98                                       | 2.70                                        | 2.14                                           |
|                      |                                   | 2.29                                       | 6.01                                        | 1.26                                           |
| 30                   |                                   |                                            |                                             |                                                |

4.2. Comparison with Results of Laboratory Tests

According to collapse coefficients of the soil samples under overburden pressure at different depths measured in laboratory tests, the collapse settlements of 16m, 30m thick foundations by layered summation method is 0.95 m, 2.14 m respectively. Therefore, the correction coefficient for measured data due to soil quality is 1.26, which is higher than the value specified in code 50025. There are many reasons why the measured correction coefficient is significantly higher. Firstly, the value of $\beta_0$ specified in code 50025 is based on previous studies and existing engineering data which didn’t include the actual collapsible data of Yili Region in Xinjiang at that time. Secondly, the thickness of the collapsible soil is large and its erosion-resistance is low. Thirdly, the stress condition in laboratory tests is inconsistent with that of field immersion tests.

5. Summary

In this paper, the collapsible characteristics of the loess foundation under overburden pressure were studied by centrifugal model tests. The main conclusions are as follows.

1) In order to study the effects of saturation methods on foundation collapse, soil samples are saturated using gas pumping saturation method, low pressure saturation method and water film transfer method, respectively. Collapse settlement of different saturated foundations based on double line method is obtained. Comparing the foundation collapse obtained from the field testing results and centrifugal model testing results, the centrifugal model test results using low pressure saturation method is very close to the field immersion test results with a relative error of 3%. This indicates that it is more reasonable to use low pressure saturation method to simulate the collapse deformation of loess in this region based on double line method. And it’s feasible to use centrifugal model tests to simulate field immersion tests.

2) The correction coefficient for measured data due to soil quality in Yili Region is 1.26 by comparing the calculated data with the field measuring data, providing a basis for soil studies in Yili Region in the future.

Acknowledgements

This research was financially supported by the National key research and development program of China (Grant No. 2017YFC0804600).

References

[1] Code for Building Construction in Collapsible Loess Region(GB50025-2004), China Architecture & Building Press, Bei Jing, 2004.(in Chinese)

[2] X. F. Huang, Z. H. Chen, Sh. Ha. Large area field immersion tests on characteristics of deformation of self-weight collapse loess under overburden pressure, Cn. J. Geo. Eng., 28, 382-389(2006).(in Chinese)
[3] C. D. F. Rogers and T. A. Dijkstra. Hydroconsolidation and subsidence of loess: Studies from China, Russia, North America and Europe, Eng. Geol., 3783-113(1994).

[4] L. S. Deng, W. Fan, Y. P. Yin, Y B Cao. Case study of a collapse investigation of loess sites covered by very thick loess–paleosol interbedded strata, Int. J. Geomech., 11, 05018009-1-18(2018).

[5] X. L. Wang, Y. P. Zhu, X F Huang. Field tests on deformation property of self-weight collapsible loess with large thickness, Int. Int. J. Geomech., 3, 04014001-1-8 (2014).

[6] C. L. Zhang, T. L. Li, P. Li. Rainfall infiltration in Chinese loess by in situ observation, J. Sci. J. Hydro. Eng., 9, 06014002-1-3 (2014).

[7] F. X. Yan, X. Z. Huang. Dynamic and Static Mechanical Properties of Loess Subgrade in Shanxi, Adv. Soil. D. F. 39-44(2014).

[8] M. J. Jiang, J. S. Ma, Y. J. Cui, etc. Experimental investigation of the deformation characteristics of natural loess under the stress paths in shield tunnel excavation, J. Sci. Int. J. Geomech., 9, 04017079-1-10(2017).

[9] Y. L. Du, & L. B. Han. Geotechnical centrifuge model test technology, China's Water Conservancy and Hydropower Press. Beijing, 2010. (in Chinese)

[10] Y. Uchita, T. Shimpo, V. Saouma. Dynamic centrifuge tests of concrete dam, Earthq. Eng. Struct. D. 34,1467-1487(2005).

[11] S.W. Jin, Y. W. Choo, Y. M. Kim, D. S. Kim. Centrifuge Modeling of Differential Settlement and Levee Stability due to Staged Construction of Enlarged Embankment, J. Civ. Eng., 18, 1036-1046(2014).

[12] C. M. Gong, Q. G. Cheng, Z. P. Liu. Centrifuge model tests on excavation and reinforcement effect of loess slope, J. Rock. & Soil. Mech., 31, 3481-3486(2010). (in Chinese)

[13] D. S. Kim, N. R. Kim, Y. W. Choo. A newly developed state-of-the-art geotechnical centrifuge in Korea, J. Civ. Eng., 17, 77-84(2013).

[14] Z. D . Cui, Y. J. Jia. Analysis of electron microscope images of soil pore structure for the study of land subsidence in centrifuge model tests of high-rise building groups, Eng. Geo., 164, 107-116( 2013).

[15] C. D. Wang, X. Wang, S. H. Zhou. Centrifugal model tests on self-weight collapsible loess and negative skin friction of pile foundations, J. Ei. Cn. J. Rock. Mech. & Eng., 29.;3101-3107(2010).(in Chinese)