Discussion on Assessment in the Collapse of Loess: A Case Study of the Heifangtai Terrace, Gansu, China

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Abstract

Collapsibility is a unique feature of loess. Besides foundation deformation and subsurface erosion, slope failures can also be resulted from the collapse of loess. Based on analysis of the collapse of loess at the Heifangtai terrace, Gansu, China, a notable difference between the theoretically calculated and actual values of collapse were observed. The theoretical value was less than 50 % of the actual one. Based on this difference, the assessment of the collapse of loess, including definition of collapsible loess and calculation of the collapse are discussed. It is found that collapsible loess is a kind of typical unsaturated soil. Therefore, water content and types of structures were essential factors affecting the collapsibility of loess. Assessment of the collapse of loess, from *why collapse* to *how collapse,* can be achieved by applying parameters representing both water content and types of structure, using the theory of unsaturated soil mechanics.

Keywords

Loess • Collapsibility of loess • Irrigation • Groundwater

Introduction

Loess is a kind of sediment with special physical and mechanical property which is widely distributed in the world (Sun 2005). It covers an area of at least 640,000 km^2, that is, approximately 6.6 % of the total land area in China, of which three-quarters is collapsible loess (Luo 1998). Loess, especially the collapsible loess, is highly porous sediment which can sustain nearly vertical slopes when dry but subject to catastrophic failure on reaching certain critical moisture contents (Derbyshire et al. 1997, 1999). Collapse of building foundations in collapsible loess distributed area and consequent cracking of walls is common, and has affected a number of cultural heritage sites (Derbyshire et al. 1997).

Research on the collapse of loess has been conducted by scientists who focus on the engineering properties of loess for more than half a century. From the view of interpreting the reason of the collapse of loess, theories pertinent to hypotheses on soluble salts (Muxart et al. 1995), colloid deficiency and capillary effect (Dudley 1970), under-consolidation of soil and structural effect (Zhang 1964, Zhang et al. 1985; Lei 1987; Gao 1980; Locat 1995), and mechanics of loess (Liu 1997; Chen and Liu 1986; Fredlund et al. 1995) have been proposed. To deal with the practical problems related with the distinctive behaviour of loess, four national standards have been issued in China from 1966 to 2004, where engineering zonation and classifications have been developed for use in regional planning. In the latest one (GB 50025–2004), issues related with types and definition of collapsible loess, and foundation treatments have been improved, with which the engineering projects in collapsible loess distributed areas have been well guided.

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However, most of the previous studies are descriptions of the collapse phenomenon in loess based on the theory of saturated soil. In fact, the collapse of loess in saturated soil is just a special case. It usually occurs at different depth of soil with various water contents (Xie 1999). From the unsaturated soil point of view, Barden et al. (1969) conducted the collapse test of consolidated soil under unsaturated and constant suction condition. Tang (2003) believes that both the synthetic effect of microstructure and uneven suction contribute to the collapse. Yuan et al. (2007) hold the opinion that the collapse of loess is resulted from the decrease of suction stress. Xu and Dai (2009), Xu et al. (2009) introduced a generalized definition of the collapsible loess from the view of unsaturated soil. The theoretical understanding of the collapse of loess is more close to reality from the view of unsaturated soil mechanics theory. However, related studies are usually constrained from the test conditions with complex stress states, which results in great differences between the theoretical and actual values. The Heifangtai terrace was taken as an example in this paper to draw attentions of the related researchers. In this site, the actual value of collapse was more than 5.96 m while a calculated value of collapse is 2.8 m. The related problems when assessing collapsibility of loess were also discussed.

Typical Case Study for the Collapse of Loess

Background of the Study Area

The Heifangtai terrace is located 42 km west of Lanzhou city in Yongjing County, Gansu province, North-West China. The landform comprises windblown loess deposits (Upper Pleistocene), overlying the fourth terrace of the Yellow River, presently forming steep, high cliffs along the river corridor. This used to be an isolated loess platform with a very limited groundwater flow regime. However, following the construction of a major reservoir in 1963, people were resettled onto the platform. In support of this resettlement, most parts of the terrace levels have been reclaimed as farmland with extensive irrigation taking place since 1968.

There are usually five stages of irrigation per year at the Heifangtai platform. The first stage occurs in spring from March to May, the last one occurs in winter from November to December, and the other three stages occur between spring and winter. In the 1980s, the total irrigation volume was 7.22 million m^3 per year (about 0.90 m^3 per square meter). In the 1990s, this changed into 5.76 million m^3 per year (0.64 m^3 per square meter). More recently, the total irrigation volume is 5.90 million m^3 per year (0.84 m^3 per square meter).

Due to the macro-porous fabric of the aeolian loess, widespread soil collapse occurred following the irrigation. In turn, this resulted in large areas of farmland becoming discarded, most irrigation pipes being destroyed, and the dwellings requiring repair once every 3 or 4 years. Landslides along the plateau edges are also aggravated with the development of the cracks resulting from uneven settlement of the terrace surface.

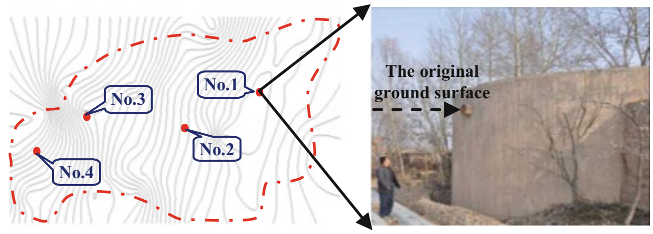

Fig. 1 Location of the water tower

Actual Value of the Collapse

The phenomenon of conversions of four subsurface cisterns into water tower (Fig. 1) aroused the authors' interest to research on the collapse of loess in the Heifangtai terrace. All the four subsurface cisterns were built at the time of construction in 1968, to meet the need of domestic water supply. Consolidation, tamping, and structural reinforcement were conducted as remedial measures to eliminate collapsibility of loess in the foundation layer. While tremendous collapse occurred to the circumjacent loess of the cisterns. Let us take the No. 1 cistern as an example. It is a cistern with a depth of 9 m, which is built with the top level with the ground surface. However, this top level is now 3.5 m higher than the ground surface due to collapse of the surrounding loess deposits (Fig. 2). This shows that for the top 9 m some 40 % of the original volume has been lost. The other three cisterns (No. 2, 3 and 4) are now in similar situation.

Based on the comparison of topographic maps between 1977 and 1997, obvious differences for the surface elevations at different years were also observed (Fig. 3). The maximum difference for the surface elevation is 5.96 m, with an average difference of 3 m. It shows that the maximum value of land settlement is 5.96 m in the past 20 years. These observations are much greater than the calculations of the collapse of loess in the previous work.

The triggering factors for loess collapse are an increase of groundwater level and infiltration of irrigation water. Based on the tested changes of coefficient of collapsibility with depth (Fig. 4), it shows that the loess layer at the Heifangtai terrace can be divided into four parts on the basis of different mechanism of collapse. Collapse induced by irrigation water occurs between depths of 0–12 m, where the coefficient of collapsibility for loess in the irrigation district differs a lot

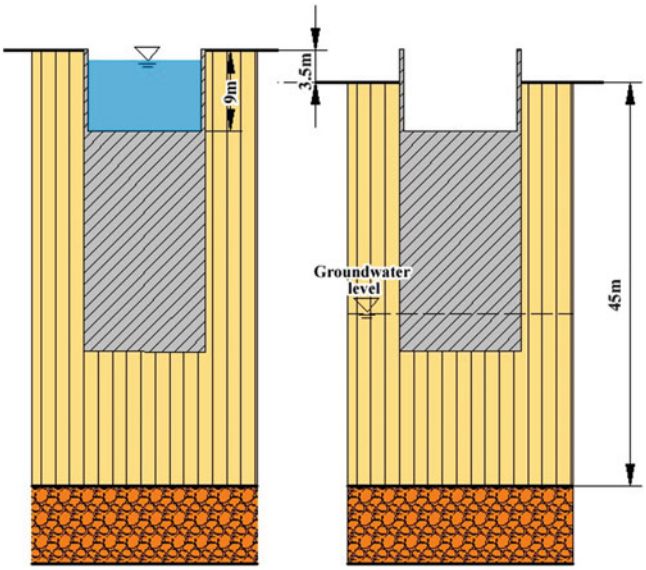

Fig. 2 Conversion of subsurface cistern into water tower

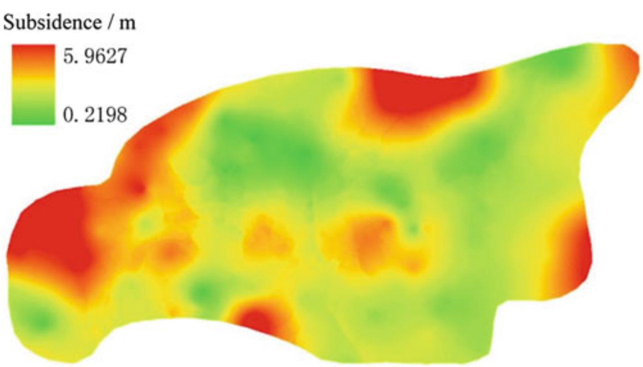

Fig. 3 Comparison of topographic maps between 1977 and 1997

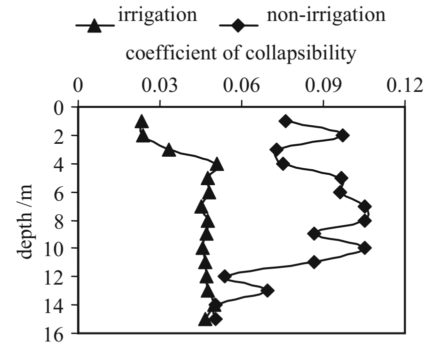

Fig. 4 Changes of coefficient of collapsibility with depth

from that in the non-irrigation district. There is no obvious collapse between depths of 12–22 m, where the coefficients are similar in both districts. Collapse induced by capillary water occurs between depths of 22–25 m, and the base of the loess, between 25 and 45 m, is saturated and collapsibility potential can be neglected.

Theoretical Value of the Collapse

The collapse of loess at the study area was self-weight collapse without applied load because most parts of the terrace level have been reclaimed as farmland since 1968. Wells with depth of 15 m were explored in the irrigation and non-irrigation districts. Fifteen samples were collected in each well, with one sample per meter to test the collapsibility of loess, and the averaged values were listed in Table 1.

Table 1 shows that there is still large collapse potential for loess in the upper 15 m, especially for the loess in non-irrigation district. The average value of the coefficient of collapsibility for loess in the irrigation district is 0.0443, indicating a high potential for collapse, even though it has experienced irrigation for more than 40 years. Based on the information from surrounding wells, loess layer thickness across the irrigation district is approximately 45 m where collapsibility for saturated loess in the lower 20 m is negligible. However, loess layer thickness across the non-irrigation district is 50 m. According to the guide of national standard in China (GB50025-2004), self-weight collapse of loess both in irrigation and non-irrigation districts were calculated with the layer-wise summation method. Assuming that the loess at depth from 0 to 50 m is collapsible, the calculated values of total self-weight collapse in irrigation and non-irrigation districts were 1.68 and 4.48 m, respectively. That is, the collapse of loess in the irrigation district was 2.8 m, which is less than 50 % of the actual collapse of loess.

Discussion on Assessment of Loess Collapsibility

Calculation of the Collapse

The recommended formula in the national standard (GB50025-2004) are based on the mechanism of saturated soil, without considering some essential factors affecting collapsibility of loess, such as changes of water content with depth under long-time irrigation condition, content changes of soluble salts, variations in microstructures of loess, and stress redistribution in loess. In addition, most of the methods testing collapsibility of loess in laboratory are based on lateral confinement condition, which cannot reflect the natural state of the collapse of loess under variable confinement conditions. Multiple factors contribute to the great difference between calculated and actual values of collapse.

Table 1 Coefficients of collapsibility before and after irrigation at different depth

Depth/m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	>15
δ_{z1} ($\times 10^{-2}$)	2.43	2.40	3.34	5.1	4.75	4.83	4.52	4.74	4.73	4.57	4.66	4.72	4.77	5.01	4.68
δ_{z2} ($\times 10^{-2}$)	7.63	9.73	7.30	7.5	9.67	9.63	10.5	10.5	8.69	10.5	8.65	5.36	6.93	5.03	5.04

Note: δ_{z1} and δ_{z2} are coefficients of collapsibility of loess in irrigation and non-irrigation district, respectively

Definition of the Collapsible Loess

According to the national standard (GB50025-2004), when the tested value of coefficient of collapsibility under some applied load is more than 0.015, it is defined as collapsible loess; otherwise it is defined as non-collapsible loess. This definition is suitable for loess-distributed area with small-thickness loess. However, for loess with large thickness, the collapse of loess is still not negligible even when the coefficient of collapsibility is less than 0.015 because the value of collapse from accumulation layer by layer is considerable. If the collapsibility of loess with small coefficient is overlooked in practice, tremendous negative effect on stability of buildings will occur.

Further Research Based on the Unsaturated Soil Mechanics Theory

Loess is typical unsaturated soil. Yuan et al. (2007) holds the opinion that the contribution of suction to structure strength is significant, who believes that the collapse of loess is owing to the strength decrease during the process of suction variation. Zhu and Chen (2008) also believes that collapse occur as a result of suction reduction under soaking and applied-load conditions. Based on the above description, one can conclude that water content and types of structures were essential factors affecting the collapsibility of loess. The nature of the collapse of loess can be interpreted applying parameters representing both water content and types of structure. Lu et al. (2010) introduced a parameter representing effective stress in unsaturated soil, which is a combination of water content and structures. With the advanced equipment such as TRIM introduced by Lu et al. (2010) and the combined parameter, assessment of the collapse of loess from why collapse to how collapse may be achieved.

Conclusion

1. The collapse of loess induced by long-time irrigation in the Heifangtai terrace is much greater than empirical values of previous work. The maximum value of collapse is more than 5.9 m, which is two times the calculated value. This fact indicates that assessment of the collapse of loess based on the traditional mechanism of saturated soil cannot satisfy the demands in current engineering.
2. For loess layers with large thickness, the collapse resulted from the loess with coefficient of collapsibility less than 0.015 cannot be negligible.
3. Loess is typical unsaturated soil, and water content and types of structures were essential factors affecting the collapsibility of loess.
4. Tests under complex stress state with advanced equipments are the future trend for studying the mechanism of the collapse of loess.

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References

Barden L, Madedor AO, Sides GR (1969) Volume change characteristics of unsaturated clay. J Soil Mech Found Div 95 (SM1):33–52

Chen ZH, Liu ZD (1986) Mechanism of collapsible deformation of loess. Chin J Geotech Eng 8(2):1–12

Code for building construction in collapsible loess regions (GB50025-2004) (2004) China Architecture & Building Press, Beijing

Derbyshire E, Kemp RA, Meng XM (1997) Climate change, loess and palaeosols: proxy measures and resolution in North China. J Geol Soc 154:793–805

Derbyshire E, Meng XM, Dijkstra TA (1999) Landslides in the thick loess terrain of North-West China. Wiley, England

Dudley JH (1970) Review of collapsing soil. J Soil Mech Found Div ASCE 96(SM3):935–939

Fredlund DG, et al (1995) The collapse mechanism of a soil subject to one-dimensional loading and wetting. In: Derbyshire E, et al (eds) Genesis and properties of collapsible soils, vol 486. Kluwer Academic Publishers, Netherlands, pp 173–206

Gao GR (1980) Microstructure classification and collapsibility of loess. Sci Chin 12:1203–1208

Lei XY (1987) The relationship between pore types and collapsibility of loess in China. Sci Chin Ser B 12:1309–1316

Liu ZD (1997) Loess mechanics and engineering. Shaanxi Science and Technology Press, Xi'an

Locat J (1995) On the development of microstructure in collapsible soil. In: Derbyshire E, Dijkstra T, Smalley IJ (eds) Genesis and properties of collapsible soils. Kluwer Academic, Dordrecht, pp 93–128

Lu N, Godt JW, Wu DT (2010) A closed-form equation for effective stress in unsaturated soil. Water Resour Res 46, W05515. doi:10.1029/2009WR008646

Luo YS (1998) Assessment of collapsibility of collapsible loess foundation. Chin J Geotech Eng 20(4):87–91

Muxart T et al (1995) Changes in water chemistry and loess porosity with leaching: Implications for collapsibility in the loess of North China. In: Derbyshire E, Dijkstra T, Smalley IJ (eds) Genesis and properties of collapsible soils, vol 468. Kluwer Academic, Dordrecht, pp 313–332

Sun JZ (2005) Loessology, vol 1. Hong Kong archaeological society, Hong Kong
Tang LS (2003) Synthetic effect of microstructure and uneven suction on loess subsidence. J Eng Geol 11(1):30–35
Xie DY (1999) The pat, present and future of the research on mechanical characteristics and application of loess. Undergr Space 19(4):273–285
Xu L, Dai FC (2009) Discussion on the further research in loess hydrocompaction. J Geomech 15(1):88–94
Xu L, Dai FC, Jin YL (2009) Discussion on the mechanism of loess collapsibility from the perspective of unsaturated soil mechanics theory. Hydrol Eng Geol 4:62–65
Yuan ZX, Wang KM, Wang J (2007) Discussion water collapsibility of loess considering unsaturated soil and structure characteristics of loess. Northw Seismol J 29(1):12–17
Zhang ZH (1964) Microstructure of loess in China. Acta Geol Sinica 44 (3):357–364
Zhang ZH, Zhang ZY, Zhang P (1985) Microstructure properties and collapsibility evaluation during collapse deformation of loess, vol 6, Geographical paper volume of international exchange. Geography Press, Beijing, pp 67–78
Zhu YQ, Chen ZH (2008) A new method of studying collapsibility of loess. Chin J Geotech Eng 30(4):524–528