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Influence of Pressure and Water Content on Loess Collapsibility of the Xixian New Area in Shaanxi Province, China

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ABSTRACT

More than 40% area of the Xixian New Area is a loess deposit region, and most of the loess landform is tableland and terrace where the thickness of loess is considerable large. Therefore, loess collapsibility will be the most important geotechnical problem in future foundation investigation and construction. To explore loess collapsibility in the Xixian New Area, we conducted the K_0 compression test, based on the collapsibility mechanism, which has different combinations of pressure (0~1.2 MPa) and water content (4%~Sat). Based on the σ-ε curve under different water content, we calculated the generalized collapse settlement and collapsibility coefficient of every water content under every pressure by subtracting the relevant curve from the saturated curve and analyzed the cross action of pressure and water on loess compressibility. The results show that the average collapsibility level of the northern Xixian New Area is self-weight collapsible level II, with a lower limit of 14 m. The compressibility of loess is proportional to pressure and water content. Under low water content, the collapsibility coefficient δ_s increased while the pressure increased, but under medium and high water content, δ_s will reach a peak with increasing pressure and after that, δ_s will decrease until its value is close to constant. When under the same pressure, δ_s decreases when water content increases. If set the additional strain 1.5% as collapse start criterion, then the first collapse pressure P_i will linear proportional to water content. The initial collapse water content w_i will increase sharply when pressure raises under low pressure, but w_i will reach a constant value of 26% when pressure is more than 200 kPa. This consequence will be meaningful for future geotechnical investigation and design in the Xixian New Area.

Keywords: Xixian New Area; loess collapsibility; wetting; pressure; initial collapse water content

Influencia de la presión y el contenido de agua sobre el índice de colapsabilidad de loess, en el distrito especial Xixian, provincia de Shaonxi, China

RESUMEN

Para estimar la colapsabilidad en Xixian se realizó el test de compresión (K_0), de acuerdo con el mecanismo de colapsabilidad, con diferentes combinaciones de presión (0~1.2 MPa) y contenido de agua (4%~Sat). Basado en la curva σ-ε con diferentes contenidos de agua se calcularon los coeficientes de asentamiento y colapsabilidad a partir de substracción de la curva en condiciones de saturación y analizando los efectos de presión y contenido de agua. Los resultados muestran que el promedio de colapsabilidad por su propio peso para el área de Xixian es de nivel II, con un límite bajo de hasta 14 m. La compresibilidad de loess es proporcional a la presión y al contenido de agua. Con un bajo contenido de agua, el coeficiente de colapsabilidad (δ_s) se incrementó mientras la presión se aumentó; pero, con contenidos medios y altos de agua, el coeficiente de colapsabilidad alcanzó su pico con el incremento de la presión, y luego bajó para prácticamente estabilizarse. Bajo presión constante, la colapsabilidad descendió al aumentar el contenido de agua. Si se asume como criterio inicial de colapso (P_i) una deformación adicional de 1.5%, P_i es linealmente proporcional al contenido de agua. El contenido de agua inicial de colapso (w_i) se incrementa drásticamente cuando la presión se eleva a baja presión, sin embargo, el contenido de agua alcanza un valor constante de 26 % cuando la presión es de más de 200 kPa. Estos resultados son significativos para la investigación geotécnica y el diseño estructural en Xixian.

Palabras clave: Distrito especial de Xixian (China); colapsabilidad de loess; humectación; presión; contenido de agua incial de colapso.

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1. Introduction

China's Loess Plateau is a vast territory with a large population. However, since the late Quaternary, the climate and ecological environment in this area have been deteriorating, resulting in frequent loess disasters, which seriously restrict economic development and urban construction (Zhang, 1980; Abbasi et al., 2017). Loess is a special soil that has a loose structure, high porosity and collapse and vibration sensitivity (Derbyshire, 1995). Therefore, the study of collapsible loess plays an important role in urban construction in the loess area. Because of its special overhead pore structure and high sensitivity of its microstructure to interactions between water and force, aeolian loess has significant collapsibility. Previous researchers (Rabinovich & Urinov, 1974; Kozubal & Steshenko, 2015) have studied the collapsibility of loess. Gao (1980) and Lei (1987) came up with a classification for loess microstructure that achieved good results, which has been used up to today. Many scholars (Zhenghan & Zudian, 1986; Yang, 1988; Miao, 1999; Wang & Gu, 2013, Zhang, 2000; Bakar et al., 2017) conducted an in-depth study of the mechanism of collapsible deformation of loess. Chinese studies (Zhang, 1995; Liu, 1997; Zhang, 2000; Ma, 2014; Usman et al., 2017) developed research on engineering properties of loess in China. In engineering practice, a standardized evaluation and treatment system has been established by collapsibility and lower limit depth (People's Republic of China National Standard for Building Construction in Collapsible Loess Area GB 50025-2004). However, from the above common features, the engineering properties of loess in China have regional characteristics (Bata et al., 2017). Differences in spatial distribution of loess deposits, provenance differences, and a series of physical and chemical reactions that differ from region to region after deposition affect the microstructure characteristics of loess and change its macroscopic physical and mechanical properties.

More than 40% area of the Xixian New Area is a loess deposit region. Most of the loess landforms are tableland and terrace where loess thickness is very large. Therefore, loess collapsibility is the most important geotechnical problem in future foundation investigation and construction. As a new state-level development area, the Xixian New Area is an important part of the western development and is the integration of Xi'an and Xianyang. It is also an important link in the strategy of building an international metropolis. The Loess Plateau area in the northern part of the Xixian New Area will allow the development of logistics and cultural tourism industries around the existing Xianyang Airport (Airport Metro) and historical and cultural scenic spots (Qin and Han dynasties). The scale and span of construction in this area will expand rapidly with an influx of investment over a short period. The number and scale of original construction located in the Loess Plateau area in the northern part of the Xixian New Area is small and large portions to be developed are still farmland; therefore, we have accumulated less basic engineering-related data in this area. Meanwhile, there is little research on the engineering properties of loess in this area. Also, the engineering properties of loess vary in space. Therefore, studying the collapsibility of loess in the Xixian New Area will have significant application value and scientific significance (Gao et al., 2017).

The traditional collapsibility of loess is the nature of the additional settlement caused by the saturation of saturated loess when the deformation of loess under certain pressure is stable. To deepen the understanding of the mechanism of loess collapsibility, some researchers (Zhang, 1990, 1992; Sun & Liu, 2000, Francisca, 2007; Yasin et al., 2017) have studied the collapsible deformation of loess during the processes of humidification and dehumidification. The definition of collapsibility is extended to the nature of additional settlement of loess by humidification under a certain pressure to form a stable deformation (Yew & Rahim, 2017). The collapsible deformation of loess is considered a kind of plastic deformation, and the amount of collapsible deformation is related to the state of humidification (Hussin et al., 2017). It is independent of the infiltration path, which indicates that loess has a memory of moistening deformation under certain pressures. However, the amount of humidification deformation and its variation law in loess are both different from the soil, so it is impossible to establish a relational expression for calculating deformation (Ismail et al., 2017; Sarkar et al., 2017). Based on this, we carried out a pre-investigation of loess in the Xixian New Area, and the K0 test for the typical horizon under different water content and pressure. The purpose of the study is to provide reference and scientific guidance for future engineering investigation and design in the loess distribution area in the northern part of the Xixian New Area (Tariq et al., 2017; Tunggolou & Payus, 2017).

2. Test Schemes

2.1 Physical parameters of soil foundation

The study area is located between the cities of Xian and Xianyang. The location of this area in Shaanxi Province is shown in Figure 1. Five exploratory wells as the cross-shaped of the five endpoints were placed on the large thickness Loess Plateau in the north of Xixian New Area (as Fig. 1), and the depth of exploratory wells is 30 m. The sampling (Fig. 2) and testing of the T1, T2, T3, T4 and T5 exploration wells were completed by the State Key Laboratory of Continental Dynamics in the Northwest University of China (Fig. 3). T1, T2, T3 and T5 exploration wells were located in the Loess Plateau, and T4 was located in the Second Terrace of the Weihe River. By comparing the five groups of experimental data, we found that the T4 site was a site of first-grade self-weight collapsibility. Also, the four sites in the Loess Plateau are sites of second-grade self-weight collapsibility. Moreover, the closer a sampling point is to the center of the Loess Plateau, the greater the amount of collapsibility and self-weight collapsibility and the deeper the depth of collapse. Although the amount of collapsibility and self-weight collapsibility in each sampling site are different, the homogeneity of soil samples at a depth of 5 m is higher, which is shown in Table 1. Therefore, selected the MaLan loess located 5 m deep at the T3 site near the Xianyang Airport as the representative layer. We further studied the influence of pressure and water content on the collapsibility of loess in the Xixian New Area.

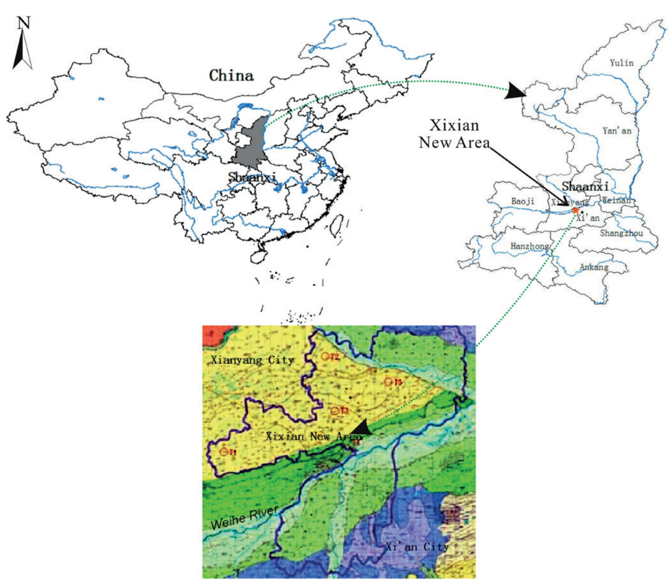

Figure 1. The sketch of location, landform, and sample diagrammatic in Xixian New Area

Figure 2. Sampling in site exploration wells

Figure 3. Automatic air pressure consolidation instrument (GZQ-1)

At T3, two 6-m-deep exploratory wells were re-excavated, and 40 soil samples were taken from the borehole wall at 5 m. In the field, the soil samples were sealed with plastic wrap to keep moisture content unchanged and then wrapped in bubble film as a buffer. Basic physical and mechanical parameters tests were carried out immediately after samples were transported to the laboratory. These tests measured the natural density, dry density, plastic limit, liquid limit, plastic index, liquid index, void ratio, water content, compression coefficient, compression modulus, the coefficient of collapsibility and coefficient of self-weight collapsibility of soil. The collapsibility test used the single line method.

Table 1. Physical and mechanical properties of Ma Lan loess at a depth of 5 m in each sampling well

Exploration number	Natural moisture Content w_0	Natural Density ρ_0	Void ratio e	Liquid limit w_L	plastic limit w_P	plastic index I_P	collapsibility coefficient δ_s	Self-weight collapsibility coefficient δ_{zs}	collapse settlement Z	Self-weigh t collapse settlement Zs	depth limit m	collapsibility degree
T1	18.4	1.54	1.08	31.0	18.4	12.6	0.024	0.008	36.79	20.43	15	II
T2	18.6	1.52	1.11	31.3	18.3	13.0	0.022	0.007	27.09	11.61	14	II
T3	18.02	1.53	1.083	31.0	18.5	12.4	0.017	0.008	29.29	12.6	15	II
T4	18.6	1.52	1.11	31.0	17.4	13.6	0.018	0.005	22.95	6.21	13	I
T5	18.8	1.54	1.08	31.6	18.0	13.6	0.019	0.005	25.69	9.72	14	II

2.2 High-pressure K_0 compression test scheme for loess with different water content

To explore the effects of interaction between water content and pressure on the compressibility of undisturbed loess in the Xixian New Area, we designed a K_0 compression test scheme with ten kinds of water content and nine levels of pressure (see Table 2). The preparation methods of soil samples with different water content are as follows. First, we cut ring-knife samples from massive soil samples at the site. Each sample was 2 cm high and had a surface area of 50 cm^2. We tested soil moisture content in the upper and lower parts of the ring-knife sample and took the average value. Based on the moisture content of each sample, we calculated the amount of water that needed to be increased according to the target moisture content. To ensure uniform moisture content, we dropped water into soil samples that needed wetting, with 6 g/d as an upper limit. Soil samples that are necessary to be dehumidified were uniformly dried to a lower water content (about 3.5%). Then we calculated the current water content according to the sample's measured mass. Finally, we prepared soil samples using the same humidification method. We prepared saturated soil samples by saturating the soil sample with the natural water content after the first stage pressure compression. To prevent a humidity difference between permeable stone, filter paper and soil samples from affecting humidity test results, we put the permeable stone and filter paper into the soil, which was mixed with water to the same water content as in Table 2 after being dried to reach a humidity balance. The test instrument was an automatic air pressure consolidation apparatus (GZQ-1 type) produced by Nanjing Soil Instrument Factory (Fig. 3), and the test methods refer to 'the standard of soil test methods' (Highway Research Institute of Ministry of communications GB/T 50123 - 1999 geotechnical test method standard).

Table 2. K_0 compression test scheme

Number	Test moisture content w	Increasing water Δw	Pressure level P
1	4%	w_0-14%	50、100、
2	7%	w_0-11%	
3	10%	w_0-8%	150、200、
4	13%	w_0-5%	
5	16%	w_0-2%	300、600、
6	19%	w_0+1%	
7	22%	w_0+4%	800、
8	25%	w_0+7%	
9	28%	w_0+10%	1000、 1200
10	Saturated	w_0+22%	

3. Test results and analysis

3.1 Effect of pressure and water content on compressive deformation properties of loess in the Xixian New Area

The relation curves of pressure and strain at different levels of water content (Fig. 4) and the curves of water content and strain under different levels of loess pressure in the Xixian New Area (Fig. 5) were all obtained using the K_0 test with 10 kinds of water content and 9 levels of pressure. The bivariate trend surface of compressibility coefficient, water content and pressure are plotted based on the two sets of data

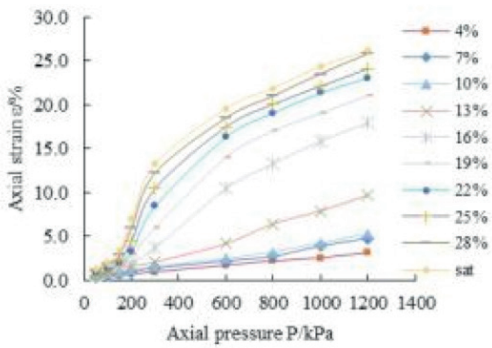

Figure 4. P-ε curves of loess under different water content

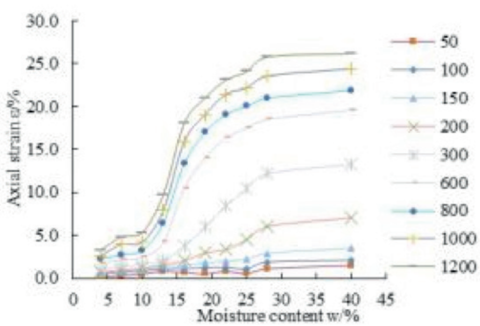

Figure 5. w-ε curves of loess under pressure at all levels

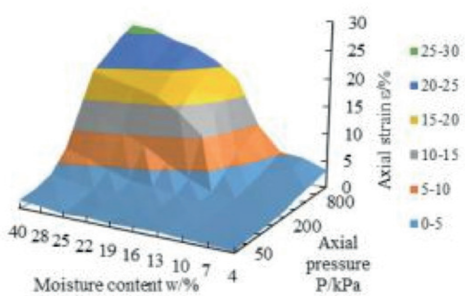

Figure 6. Bivariate trend surface of compressive strain and water content, pressure of loess

As Figure 4 suggests, compressive deformation increases with the increase of pressure at all levels of water content, but the increasing regularity with increasing water content is different. Under the low water content conditions (4%, 7%, and 10%) the P- ε curves of loess in the Xixian New Area are linear. As the water content increased to 13%, the P-ε curve began to show an inflection point, which indicated the axial strain increased significantly with the increase of pressure, and the shape of the curve changed from linear to S-sharped. The position of the pressure value corresponding to the inflection point decreased with increased water content. This phenomenon reflects a law that the mechanical stability of loess microstructure decreases as water content increases.

As Figure 5 suggests, compressive deformation increases with the increase of water content at all pressure levels, but the increasing regularity with increasing pressure is different. Under low-pressure conditions (50, 100 and 150 kPa), when moisture content increases from 4% to 40%, strain increases linearly. With the increase of pressure, the w- ε curve, similar to the P-ε curve, also began to show an inflection point. The water content corresponding to the inflection point decreases as pressure increases, and the rise of water content means a decrease in suction. This phenomenon reflects a law that the water stability of loess microstructure decreases with increasing pressure.

As Figure 6 suggests, pressure and water content affect the compression deformation of loess. In general, there is a positive correlation between water content, pressure and compression deformation. These two factors and the compression coefficient form a three-dimensional trend surface similar to a 'loess hill' in which the lower part is gentle, the middle is steep, and the top is smooth again. The gentle lower part indicates that humidification under low-pressure conditions and compression under low water content conditions will not cause a large compressive deformation. The steep middle shows that humidification under middle-pressure conditions and compression under middle water content conditions will cause compressive deformation to increase significantly. The recovery of the smooth slope at the top indicates that the growth of this compressive strain was restored to a gentle trend under high pressure and high-water content.

3.2 Effect of pressure and water content on compressive deformation properties of loess in Xian New Area

The data in Figure 4 are equivalent to carry out nine sets of double wire test of soil samples with different initial water content. The difference of strain was obtained by subtracting the compression curves of unsaturated soil samples under nine levels of water content from the full compression that is loess collapsibility. The relation curves of loess collapsibility coefficient and pressure at different levels of water content are plotted in Figure 7, which shows relation curves between collapsibility coefficient and water content of loess under different pressure levels

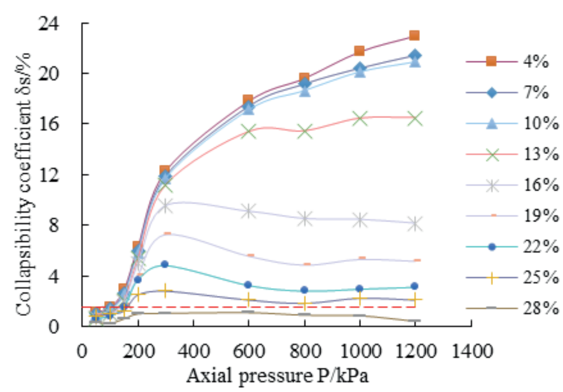

Figure 7. P-ε curves of loess under different water content

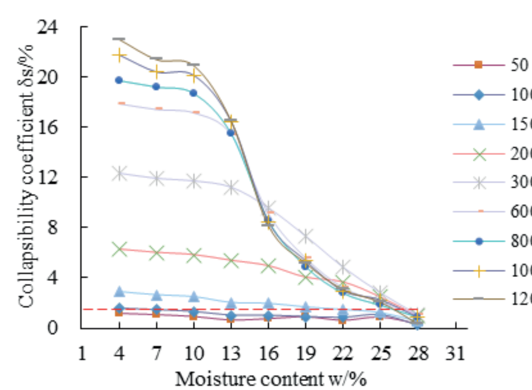

Figure 8. δs-w curves of loess under different pressures

As Figure 7 suggests, under low water content conditions (4%, 7%, 10%, and 13%), as pressure increases, the loess collapsibility coefficient in the Xixian New Area increases slowly at first, then decreases gradually after reaching a particular pressure, and finally, the growth rate gradually slows down. The δs-P curve is a sigmoid. Under medium-high water content conditions (16%, 19%, 22%, 25% and 28%), as pressure increases, the collapsibility coefficient increases to a peak value and then decreases, eventually becoming constant. The reason for this phenomenon is that the strength of the cement in the skeleton and particles of loess is larger under low water content conditions, and the effective stress caused by matrix suction on the particles is larger, which leads to an increase in friction between particles. Therefore, the strength and stiffness of soil microstructure are lower under low water content conditions, and an increase of pressure cannot do a large amount of damage to loess pore structure. Finally, the compression deformation is small before soaking. If the deformation of saturated soil under pressure at all levels is the total macroscopic deformation of the deformable microstructure under that pressure, the amount of deformation before saturation will be smaller, the amount of collapsibility after saturation will be greater, and the corresponding coefficient of collapsibility will also be greater.

For soil samples under high water content conditions, as water content increases, the infiltration of water will weaken the contribution of the cement and matrix suction to the stable state of the particles. The collapsibility coefficient increases as pressure increases before the pressure has not reached the microstructural strength at this saturation state. However, when the pressure exceeds the micro structural strength at this saturation state, the large amount of deformation of the compression stage is caused by a large amount of destroyed overhead pore structure. Once the structural strength is exceeded, deformation increases as pressure increases and the proportion of the total deformation is larger. Finally, the collapsibility coefficient decreases as pressure increases.

As Figure 8 suggests, the collapsibility coefficient decreases with the increase of water content at all pressure levels. When loess is under the combined action of certain pressure and soaking saturation, the adjustable upper limit of pore structure is the total strain of saturated soil under this pressure. The whole strain is composed of compression deformation before saturation and collapsible deformation after saturation. The reasons for the decrease of the collapsibility coefficient with the increase of water content are as mentioned earlier. Under constant pressure, microstructure strength decreases as soil moisture content increases, and the deformation is greater in the pre-compression stage. After that, the proportion of the deformation in the collapse stage (i.e. the collapsibility coefficient) will be reduced accordingly.

The initial collapse pressure is a crucial parameter in the investigation and design of a collapsible loess foundation and takes an additional settlement caused by saturation of more than 1.5% as the criterion of collapsibility. Based on the data in Figure 7, we used an interpolation method to calculate the initial pressure, Pi, of the collapsible loess at all levels of water content and then draw the curve of Pi with water content (Fig. 9). Meanwhile, based on the data in Figure 8, we used an interpolation method to calculate the initial water content, wi, of the collapsible loess at all levels of pressure and then draw the curve of wi with pressure (Fig. 10).

As Figure 9 suggests, the initial pressure of loess collapsibility in the Xixian New Area increases linearly as water content increases. This phenomenon is due to the compressibility of soil rising as water content increases. Therefore, with the increase of water content, a part of the adjustable overhead pore structure can be compressed before it reaches saturation, and to produce more than 1.5% of the collapsible strain after soaking, a greater axial pressure is required. As Figure 10 suggests, under low-pressure conditions (100 and 150 kPa), the initial moisture content of loess in the Xixian New Area increased sharply with the increase of pressure. This shows that the microstructure of loess is more sensitive to humidification under low pressure. But after the pressure reached 200 kPa, and up to 1.2 MPa, the moisture content of collapsibility was stable at about 26%. The results show that loess is not sensitive to the lower level of humidity under high pressure. This is because porous loess structure appears to be micro arch, and the normal stress between particles increases as pressure increases before reaching the structural strength under the initial water content. Accordingly, friction resistance is also stronger, and the suction drop effect caused by low-level humidification is offset. The moisture content of 26% is the critical value of moistening deformation of loess in the Xixian New Area under pressures of more than 200 kPa. When the moisture content does not exceed the critical value, it will not produce significant collapsibility.

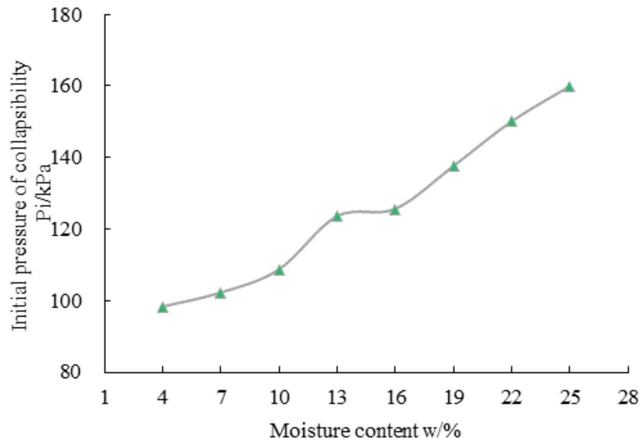

Figure 9. Relationship between the initial pressure of collapsible loess and moisture water

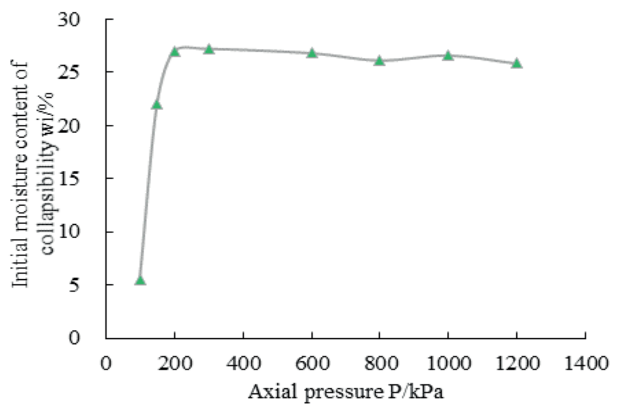

Figure 10. Relationship between initial water content of collapsible loess and pressure

4 Conclusion

Based on five representative sites in the Loess Plateau and the high order of loess deposition area reconnaissance, digging and indoor tests, we evaluated collapsibility grade of loess in the northern part of the Xixian New Area. At the same time, we carried out a special experimental study on the collapsibility of typical loess stratum. Conclusions are as follows:

1. We found that the T4 site was a site of first-grade self-weight collapsibility. In addition, the four sites in the Loess Plateau are sites of second-grade self-weight collapsibility. Meanwhile the closer to the Loess Plateau hinterland, the larger the collapsibility of the site, which makes for a lower depth of collapsibility.

2. Pressure and water content affect the compression deformation of loess. In general, there is a positive correlation between water content and pressure. These two factors and the compression coefficient form a surface with an initial gentle slope, a steep slope in the middle, and return to gentle slope surface at the top. The surface has a shape similar the 'loess hill' three-dimensional trend surface.

3. Under the same water content, when wi was lower (4%, 7%, 10% and 13%), the coefficient of collapsibility of loess in the Xixian New Area increased slowly as pressure increased, and then the coefficient of collapsibility increased sharply. Finally, the growth rate slowed down gradually. At the same time, the δs -P curve was S shaped. For middle and high water content (16%, 19%, 22%, 25%, and 28%), the collapsibility coefficient increased to a peak value as pressure increased. Then it began to decrease and tended to increase with increasing pressure. Under the same pressure, the collapsibility coefficient decreases gradually as moisture content increased.

4. If the additional settlement is greater than 1.5% for collapsibility criterion, the initial pressure of loess collapsibility increases linearly with the increase of water content in the Xixian New Area. However, the initial moisture content of collapsibility increases sharply with the rise of pressure at low pressure (100 and 150 kPa). Additionally, when the pressure is between 200 and 1.2 MPa, the moisture content of collapsibility is stable at about 26%.

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