Study on Discharge Water with Consolidation of Clay Soil on Top of Confined Aquifer

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Abstract. Consolidation and drainage tests were carried out for undisturbed saturated soil with a buried depth of 70~100m in Fuyang region. Automatic triaxial apparatus was used for tests as it can provide big confining pressure, and solve the problem of seepage along side wall, which happens with varying water head permeameter. Test results show that with continuous increase of confining pressure, water volume discharged due to consolidation of deep saturated clay is not equal to soil volume compressed. Expansion effect of soil volume takes place. And permeability of soil decreases as an exponential function with the increase of confining pressure. Stabilization of soil permeability generates time-lag effect. The test results will affect simulation of ground settlement with regard to water volume supplied by released water due to consolidation of clay in confined aquifer for shallow aquifer.

Introduction

A large number of researches were performed on land subsidence caused by excessive pumping of groundwater. With more and more wide exploitation and utilization of confined aquifer, regional land subsidence of large scale caused by excessive pumping of groundwater becomes a difficult problem to be solved. For example, scholar Ye Shujun did profound study on land subsidence due to pumping of groundwater Shanghai region [1]. The decrease of confined aquifer water level leads to the increase of soil effective stress, then clay layers at the bottom of aquifer and on the top of aquifer are compressed and water is discharged. Part of weakly bound water will join seepage flow and supply water for confined aquifer. Meanwhile, consolidation of clay layer will cause change of permeability of soil. The water volume supplied by clay layers for confined aquifer, and the change of permeability of clay layers affect the simulation of groundwater flow [2], therefore has an impact on the calculation of land subsidence and accuracy of planning schemes of groundwater exploitation.

Because at present few studies were done on the laws of water drainage due to consolidation of clay layer on top of the confined aquifer, to further discuss the topic, the Paper took deep silty clay on top of the second confined aquifer with a buried depth of 70~100m in Fuyang region as the study object, Consolidation tests and permeability tests were carried out by utilizing automatic triaxial apparatus. Based on testing results, soil volume compressed, water volume discharged and the permeability of soil under external pressure were discussed, and experimental basis is provided for the calculation of water volume supplied by deep clay layers for aquifer in the computation of land subsidence.

Method

Nowadays in the seepage calculation of silty clay, coefficient of permeability is tested by varying water head permeameter. The problem of seepage along side wall exists. Hence coefficient of permeability tested has big deviation, and measurement period is long [3,4]. But triaxial permeability measurement apparatus can solve the problem of seepage along side wall, which makes the stress state of soil samples be the natural state, and effectively makes up for the deficiencies of varying water head permeameter. Besides, triaxial permeability measurement apparatus can provide big confining pressure, which is beneficial to the measurement of water volume supplied by deep clay layers on top of the confined aquifer and coefficient of permeability. Through triaxial consolidation-permeability tests, the relationships between water volume supplied by deep clay layers, coefficient of permeability and external pressure were studied.

Characteristics of soil samples. The upper stratum at Fuyang (within 150m) is Holocene soil, which consists of silty clay, silty sand, silt and laminated medium sand and fine sand. The upper 40m is shallow aquifer. The lower stratum (from 150m to 250m) is upper Pleistocene soil, consisting of laminated medium to dense sand and silty clay. Based on the land subsidence survey carried out in Fuyang, settlement is mainly caused by groundwater exploitation from the second confined aquifer. The major contribution of settlement comes from the clay on top of the second confined aquifer. The pre-consolidation pressure ranges from 0.7 to 1.0MPa [5,6]. The undisturbed soil samples (silty clay) are derived at 70~100m below the ground level for research use. The boreholes locate at the southwest boundary of land subsidence profile of Fuyang urban area. The geotechnical parameters are derived from lab tests and are shown in Table 1.

The derived soil samples were prepared into 6 cylinder samples with height 8.0m and diameter 3.19cm. Sample *a1, a2 and a3* were used for consolidation test and sample *b1, b2 and b3* were used for permeability test. Samples were saturated by applying a back pressure and immersed in water for 24h.

Schemes and procedures of consolidation tests. Automatic triaxial apparatus with maximum confining pressure 2.0MPa and maximum axial load 30kN was used in the tests. The main equipment includes the system for stabilizing water pressure and airtight container for test specimens. The soil samples were installed according to requirements for triaxial tests in "Specification for Soil Test". Impermeable plates are placed at the water inlet.

Firstly, for sample *a1*, confining pressure is applied till a constant value P is reached. The sample *a1* is compressed and consolidated. The system for stabilizing water pressure pumps water into the airtight container to keep confining pressure P unchanged. The water volume pumped in is equal to the soil volume compressed. Due to the consolidation of soil sample, water drains out to the system for stabilizing water pressure and the water volume can be read. After the water volume pumped in and the water volume drained out keeps unchanged, tests for the next level of confining pressure will be carried out. The confining pressure has an initial value 0.9MPa, and gradually increases by 0.1MPa to the final value 1.6MPa. There will be 7 rounds of load tests. For sample *a2* and sample *a3*, the same operation will be repeated.

Table 1 Engineering geological parameters of testing samples

Bore holes	zK-3	zK-4	zK-5	zK-6
buried depth of soil samples m	70.0	80.0	90.0	100.0
water content w/%	22.2	25.6	34.6	22.2
total density g/cm3	2.01	1.98	1.86	2.02
dry density g/cm3	1.64	1.58	1.38	1.65
void ratio *e*	0.665	0.728	0.986	0.648
degree of saturation Sr/%	91.1	96	96.2	93.2
specific gravity Gs	2.73	2.73	2.74	2.72
liquid limit WL/%	38.1	38.5	50.3	36.3
plastic limit Wp/%	22.1	22.3	27.6	21.3

Schemes and procedures of permeability tests. In common falling head permeability tests, soil samples are usually put in a rigid circular container. The method will cause seepage along the interface between the container and the sample. While in triaxial permeability tests, flexible rubber membrane replaces the rigid ring. Due to the compression in triaxial cell, the rubber membrane will have tight contact with samples, which reduces the possibility of seepage along the interface to the minimum.

SLB-1 type triaxial compression apparatus of stress and strain control was used in the tests. The soil samples were installed according to the requirements for triaxial tests in "Specification for Soil Test".

The main equipment includes the system for stabilizing water pressure and airtight container for test specimens. The principles of the tests are as follows: firstly, confining pressure is applied to the test specimen till a constant value is reached. Then adverse pressure is applied as the inlet water head. And outlet water head is provided by the amount of water drained out. Therefore pressure differences, which make liquid pass through the specimen and permeate, develop between the two ends of test specimen. In the tests, after water drainage and soil consolidation develop fully, permeability tests under constant water head are carried out. When the tests are completed, confining pressure and adverse pressure are released, water in pressure chamber is discharged, radius and height of the soil sample at the time are measured, and the coefficient of permeability of clay is calculated. Coefficients of permeability under confining pressure 1.0MPa, 1.1MPa, 1.2MPa, 1.3MPa, 1.4MPa, 1.5MPa and 1.6MPa for 3 soil samples are measured respectively.

Result analyses of consolidation tests

Change of soil volume and water volume under external pressure. There are strongly bound water, weakly bound water and free water in deep clay. When soil is compressed and volume change occurs, it is free water that is discharged. With the pressure borne by soil growing to a critical value, weakly bound water in the soil starts to drain out [7,8].

During Consolidation and drainage tests, as external pressure increases, weakly bound water will join pore water seepage flow when external pressure is bigger than the shear strength t_f of it. Because the shear strength t_f of strongly bound water is much bigger than that of weakly bound water, under external pressure it will hardly leave soil. Hence, strongly bound water is not taken into account in the study [9]. Under external pressure, it is weakly bound water with small shear strength t_f that joins seepage flow. And as shown in Fig1, the drainage of weakly bound water causes that water volume discharged is bigger than soil volume compressed during soil consolidation [10]. Continuous increase of external pressure causes that part of weakly bound water join pore water seepage flow and convert to free water and drain out. And water volume discharged is always bigger than soil volume compressed, the ratio of volume of weakly bound water to the total water volume discharged grows gradually. Under a level of external pressure, the loading time lasts for about 1440min.

The soil volume compressed and water volume discharged in unit time declines gradually from 10^{-3}~10^{-4} *mL* to 10^{-5} *mL*. It indicates that due to the increase of external pressure, weakly bound water converts to free water and drains out.

Meanwhile consolidation of soil takes place and void ratio *e* declines. Under the same external pre ssure, soil volume compressed and water volume discharged decreases as time passes by, and compr ession borne by soil particles becomes balanced gradually.

When external pressure increases to the next level, weakly bound water will be released continuously. And the new round of consolidation and water drainage-compressive deformation starts.

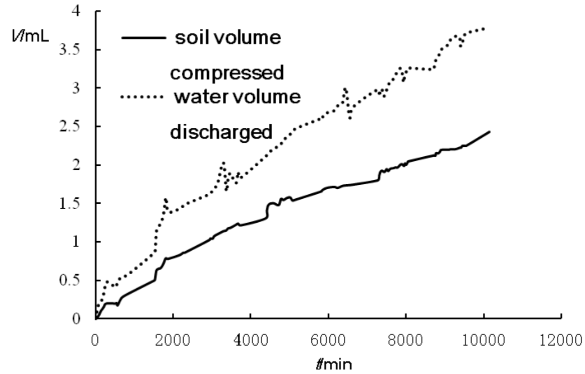

Figure 1 Variation of soil volume compressed and water volume discharged of clay

The relationship between coefficient of expansion ε and external pressure. For sample *a1, a2, a3*, with external pressure increasing, water volume discharged is always bigger than soil volume compressed, that is, expansion effect of soil volume takes place when deep saturated clay is compacted. Define coefficient of expansion ε as the ratio of water volume discharged to soil volume compressed, the variation of ε with time is as shown in Fig.2.

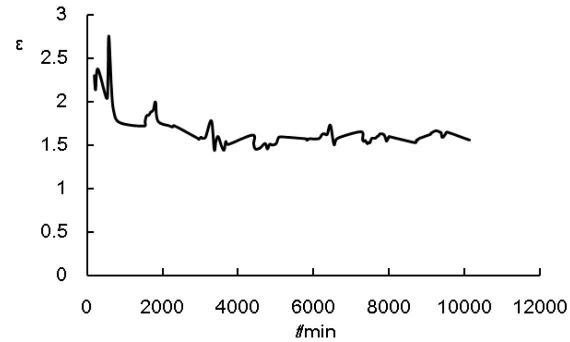

Figure 2 ε-t variation of clay during consolidation

As shown in Fig.2, with external pressure increasing gradually from 1.0MPa to 1.6MPa, coefficient of expansion ε decreases gradually from 2.75 to 1.55. When external pressure is not bigger than 1.3MPa,coefficient of expansion ε declines fast. But as the pressure grows, coefficient of expansion ε becomes stable at around 1.5. It indicates that degree of consolidation rising, even external pressure is big enough, the ratio of bound water volume to total water volume discharged doesn't increase any more. According to testing results, average coefficient of expansion ε for 3 samples are listed in Table 2. And the variation of coefficient of expansion ε with external pressure P is shown in Fig.3. It can be seen from the figure that their relationship is power function with the equation in Eq.1. The correlation coefficient reaches 0.93. Besides, with external pressure growing, the void ratio declines, and increaseing the range of coefficient of expansion ε due to drainage of weakly bound water decreases gradually. As external pressure increases continuously, coefficient of expansion ε becomes stable.

Table 2 Results for consolidation tests of deep saturated clay

External pressure *P*/MPa	1	1.1	1.2	1.3	1.4	1.5	1.6
Coefficient of expansion ε	1.72	1.68	1.62	1.59	1.57	1.56	1.56

$$e = 1.7 p^{-0.22} \quad (1)$$

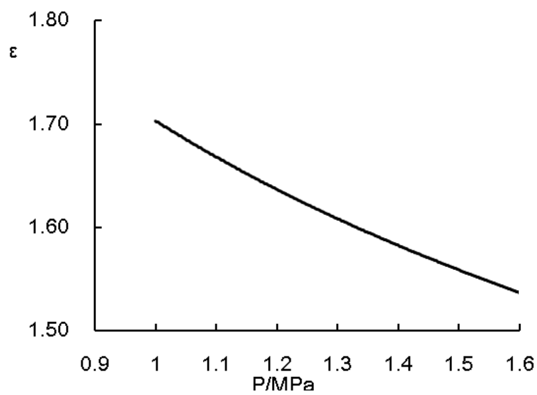

Figure 3 ε-*P* variation of deep saturated clay during consolidation

Result analyses for permeability tests

Study on characteristics of permeation. External pressure leads to the increase of soil effective stress, hence causes the change of shape, size and connectivity of void among soil particles, and then the change of soil permeability. For deep saturated clay, with degree of consolidation rising, void ratio *e* declines and coefficient of permeability *K* also changes. Average coefficient of permeability *K* for sample *b1*, *b2* and *b3* are listed in Table 3. According to testing results and as shown in Fig.4, the relationship between coefficient of permeability *K* and external pressure P is exponential function with the equation in Eq.2. When external pressure increases from 1.0MPa to 1.2MPa, coefficient of permeability *K* declines fast. After that, it drops slowly. When external pressure reaches 1.5MPa, the value of coefficient of permeability *K* becomes very small, in the magnitude of 10-10cm/s. Even if external pressure increases continuously, coefficient of permeability *K* will not change obviously.

Table 3 Results for permeability tests of deep saturated clay

External pressure *P*/MPa	1	1.1	1.2	1.3	1.4	1.5	1.6
Coefficient of permeability *K*/cm.s-1	1.32e-08	5.14e-09	3.94 e-09	3.57e-09	1.17 e-09	3.36e-10	1.68e-10

$$k = 4\times10^{-5} e^{-0.71p} \quad (2)$$

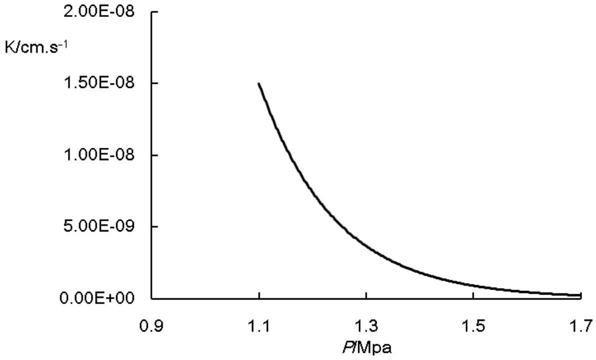

Figure 4 *K-P* variation of deep saturated clay under consolidation

Analysis of K-lgt variation. Through the tests, it can be found that as long as the loading time of external pressure is long enough, there will be a curve for K-lgt variation as shown in Fig.5. The results indicate that under some external pressure, part of weakly bound water will join pore water seepage flow and convert to free water and drain out because external pressure is greater than its shear strength. As time goes by, the volume of weakly bound water released reduces to 0. And permeation quantities decreases gradually and becomes stable after the completion of soil consolidation. Therefore coefficient of permeability *K* declines gradually till weakly bound water in soil no longer converts to free water. That is, the actual permeability of soil shows after the completion of compressive deformation, having a time-lag effect. Meanwhile, if external pressure grows, the value of coefficient of permeability *K* will be bigger than that under the last level of external pressure. The reasons are that the increment of external pressure is undertaken by weakly bound water in soil. The drainage of weakly bound water leads to the increase of permeation quantities, and therefore causes the big rise of coefficient of permeability *K*. But generally speaking, with the increase of external pressure, the coefficient of permeability *K* decreases gradually when soil is stable.

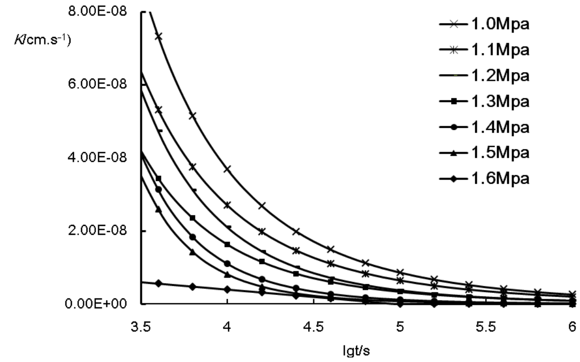

Figure 5 *K*-lg*t* variation of deep saturated clay under consolidation

Conclusions

Excessive pumping of groundwater leads to consolidation of clay layers on top of confined aquifer, hence causes land subsidence. Through consolidation-permeability tests of deep clay on top of confined aquifer in Fuyang region, it shows that under external pressure, part of weakly bound water will join pore water seepage flow and convert to free water and drain out. Therefore water volume discharged is bigger than soil volume compressed during soil consolidation, that is, during consolidation expansion effect of soil volume takes place. The coefficient of expansion decreases as power function with the increase of external pressure. As the pressure grows continuously, the coefficient of expansion becomes stable.

Before for the simulation of land subsidence, K, coefficient of permeability of clay layer on top of the confined aquifer which is impermeable or weakly permeable, is treated as a constant value. Through the triaxial permeability tests in the paper, external pressure's impact on the coefficient of permeability of deep saturated clay is studied. The results show that the relationship between coefficient of permeability K and external pressure is exponential function. When external pressure is smaller than 1.2MPa, coefficient of permeability K decreases fast. After that it changes slowly and becomes stable. But during permeation, due to the drainage of weakly bound water, stabilization of soil permeability will generate time-lag effect.

Due to the restraints of test conditions, functional relationships between coefficient of expansion, coefficient of permeability of deep saturated clay on top of the confined aquifer and external pressure are established preliminarily. Scientific basis is provided for the simulation of land subsidence in Fuyang City.

References

[1] S. Ye, Y. Xue and Y. Zhang, Study on the deformation characteristics of soil layers in regional land subsidence model of Shanghai, Chinese Journal of Geotechnic al Engineering. 27(2005)140-147. (in chinese)

[2] Y. Wang, Z. Chen, Y. Fei, J. Liu and W. Wei, Estimation of Water Released from Aquitard Compaction Indicated by Fluorine in Cangzhou, Journal of Jilin University (Earth Science Edition). 41(2011) 298-301. (in chinese).

[3] Y. Dong. The Experimental Research of the Permeating Characteristic of Saturated Cohesive Soil, Journal of Qinghai University. 17(1999) 6-13. (in chinese).

[4] H. Liu, M. Chen, A Discussion on the Amelioration of Clay Permeameter, Research of Environmental Sciences. 9(1996) 54-57. (in chinese).

[5] Z. Yang, Fuyang city in anhui province of groundwater exploitation and utilization present situation and cause of geological environment, Geology of Anhui. 17(2007) 134-139. (in chinese).

[6] Y. Li, Y. Guan and L. Sun, Trend forecast of Land subsidence in fuyang city, Hydrogeology & Engineering geology. 1(1993)50-54. (in chinese).

[7] X. Wang, C. Liu, Discussion on permeability of deep clayey soil, Chinese Journal of Geotechnical Engineering. 25(2003)308 -312. (in chinese).
[8] B. Zhang, Y. Tao and J. Zhao, The Law Analysis of Saturated Clay Discharge Water with Pressure. Journal of Jilin University (Earth Science Edition). 42(2012) 367-371. (in chinese).
[9] X. Feng, X. Shen, The seepage consolidation of saturated cohesive soil characteristics and microscopic mechanism research, Hydrogeology & Engineering geology. 18(1991):6-11. (in chinese).
[10] B. Zhang, J. Zhao and Y. Tao, The Law Analysis of Saturated Clay Discharge Water Resonse with Pressure, Chinese Journal of Rock Mechanics and Engineering. 31(2012)3203-3208. (in chinese).