Effect of Confining Pressure and Time on the Permeability of Saturated Remodeled Loess

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Abstract. The permeability of saturated remodeled loess is closely related to slope engineering and digging-filling engineering. In order to explore the permeability of saturated remodeled loess, a list of triaxial permeability test is conducted on compacted loess under different confining pressures. The results show that the permeability coefficient of saturated remodeled loess decreases with the increase of permeability time, and finally stabilizes. The variation of confining pressure in the range of low and high confining pressures greatly affects the permeability coefficient of loess. A model considering the relationship between permeability coefficient and confining pressure is given, and applied to predict the permeability coefficient of loess under different confining pressures.

Keywords. Saturated remolded loess, triaxial permeability test, permeability coefficient, confining pressures.

1. Introduction

The structure of loess is easily to be damaged by water because of loess permeability. Loess permeability is closely related to some engineering geological problems, such as landslides triggered by rainfall, foundation settlement, deformation of loess-filled foundation, etc. To explore and solve these problems, it is necessary to investigate the permeability of loess.

The permeability of saturated loess is usually described by permeability coefficient from Darcy’s law. Samarasinghe, Mesri, Xie, Nagaraj [1-5] find that there is a certain relationship between void ratio and permeability coefficient, and propose a series of nonlinear permeability models. Guo [6] conducts a series of triaxial permeability tests, and find that permeability coefficient is affected by void ratio that changes as confining pressure increases. Dorsey [7] finds that the water temperature also affects the permeability coefficient of soil. However, the permeability of compacted loess influenced by both confining pressure and time is not clear. To explore the evolution of permeability coefficient, this paper conducts a list of triaxial permeability test on saturated remolded loess under different confining pressures.

2. Triaxial Permeability Test of Remolded Loess

2.1. Test Materials

The soil is Q₃ loess that is taken from the west of shannxi province in China. It is a kind of low liquid limit soil with properties shown in table 1.
Table 1. Physical properties of the loess.

| Natural density    | Natural water content | Liquid limit | Plastic limit | Specific gravity | Optimum water content | Maximum dry density |
|--------------------|-----------------------|--------------|---------------|------------------|------------------------|---------------------|
| 1.58 g/cm$^3$      | 12.350%               | 29.73%       | 18.42%        | 2.695 g/cm$^3$   | 17.0%                  | 1.750 g/cm$^3$      |

The loess samples’ bottom diameter and height is 3.91 cm and 8.00 cm, respectively. It is crushed, dried, and passed through a 1 mm diameter screen. Then, it is tested by a laser particle size distribution instrument for grain composition, as shown in figure 1. The soil is well-graded for $C_u$ is 8.986 and $C_c$ is 1.588 [8].

![Figure 1. Grain size distribution of the tested loess.](image)

2.2. Test Method

The test instrument is TSZ-1 automatic triaxial instrument, and its confining pressure system and back pressure system are used. The effective confining pressure is the difference between the confining pressure and the back pressure; the penetrant—de-aired water—is applied to the top of the triaxial sample through the upper pressure cap, and the exudate passes through the pipe which is at the bottom of the sample. The back pressure control valve is adjusted to keep the back pressure stable, which is equivalent to the constant head permeability test.

The samples prepared in section 2.1 are encased into the confining chamber of TSZ-1 automatic triaxial instrument. Firstly, the samples subject to head saturation at confining pressure of 25 kPa and back pressure of 20 kPa. Secondly, as the water inflow equals water outflow, the samples are consolidated for 12 hours under the effective confining pressure 50 kPa, 100 kPa, 200 kPa, and 300 kPa, respectively. Finally, a list of triaxial permeability tests is conducted on the saturated remodeled loess samples. There are three parallel samples under each effective confining pressure. The permeability coefficient is obtained by:

$$k_{20} = \frac{\eta_T}{\eta_{20}} \cdot \frac{Q_L}{Aht}$$  \hspace{1cm} (1)

where $k$ is the permeability coefficient (cm/H); $\eta_T$ and $\eta_{20}$ is the coefficient of viscosity of water at T°C and 20°C (kPa*s), respectively; $Q$ is the quantity of flow at a given time interval (cm$^3$); $L$ is the height.
of the samples (cm); \( A \) is the cross-sectional area of sample (cm\(^2\)); \( t \) is the interval of time (hour); \( h \) is the height of water head (cm).

The back pressure (40kPa) is equivalent to a constant head of 4 m. The total permeability time of each sample is 130 hours. During the permeation process, the permeated water volume from the 9th hour to the 11th hour is recorded. The permeability coefficient is calculated using equation (1) and is regarded as the permeability coefficient of the 10th hour. The permeability coefficient of the 20th hour, 30th hour, etc. is calculated in this way.

3. Analysis of Test Results

3.1. Relationship between Permeability Coefficient and Permeability Time
The internal particles will migrate under the penetrating power, and the penetrant will also wash away the internal cement and damage structure. The permeability coefficient of loess decreases with the increase of permeability time and finally stabilizes [9]. The relationship between the permeability coefficient and permeability time of loess has a consistent trend with Yangling loess, as shown in figure 2.

3.2 Relationship between Permeability Coefficient and Confining Pressure
The average permeability coefficient of 110th hour, 120th hour and 130th hour is regarded as the final stable permeability coefficient \( k \). The confining pressure also has a significant effect on the permeability coefficient (figure 2). To further explore the effect of the confining pressure on the permeability coefficient, an average permeability coefficient ratio \( N_{i-j} \) is defined by:

\[
N_{i-j} = \frac{k_{u-i}}{k_{u-j}} / (i - j)
\]

where \( k_{u,i} \) and \( k_{u,j} \) is the final stable permeability coefficient of the samples under the confining pressure \( i \) kPa and \( j \) kPa (hour/s), respectively; \( N_{i,j} \) is the average permeability coefficient ratio within the range of \( i-j \) kPa.

As shown in table 2, the average permeability coefficient ratio decreases and then increases with the increase of confining pressure. Compared with the range of medium confining pressure, confining pressure greatly affects the permeability coefficient of samples especially in the range of low and high confining pressure.

![Figure 2](image-url)
Table 2. Average permeability coefficient ratio under different range of confining pressure.

| Range of confining pressure (kPa) | Average permeability coefficient ratio |
|-----------------------------------|---------------------------------------|
| 50-100                            | \(N_{50-100}=0.0846\) |
| 100-200                           | \(N_{100-200}=0.0396\) |
| 200-300                           | \(N_{200-300}=0.0941\) |

3.3. Analysis of Permeability Model

The void ratio of samples will change if the saturated remolded loess samples subject to the isotropic confining pressure. The actual void ratio of the samples is obtained by the initial void ratio and consolidation drainage volume of samples. A linear fitting is performed on the confining pressure and the actual void ratio, as shown in figure 3. The relationship of the confining pressure and the actual void ratio is expressed by:

\[ e = a \ast P + e_0 \] (3)

where \(P\) is the confining pressure (kPa); \(e_0\) is the initial void ratio; \(e\) is the actual void ratio; \(a\) is a parameter related to the properties of the soil, which is determined by experiments.

Considering the effect of void ratio on permeability coefficient, Mesri [2, 3] proposed the nonlinear permeability model:

\[ k = D e^E \] (4)

where \(D\) and \(E\) are parameters related to the properties and stress state of samples, which is determined by experiments. Curve fitting is performed on the void ratio and final stable permeability coefficient of samples using the Mesri permeability model, as shown in figure 4. The Mesri permeability model can better simulate the relationship between the void ratio and final stable permeability coefficient (\(R^2=0.9809\)). By submitting equation (3) into equation (4), and equation (5) is obtained:

\[ k^* = D \ast (a \ast P + e_0)^E \] (5)

Figure 3. Fitting curve of the actual void ratio under confining pressures.
where $k^*$ is the predicted permeability coefficient (cm/hour); $P$ is the confining pressure (kPa); $e_0$ is the initial void ratio; $D$, $a$, and $E$ are parameters related to the properties and the stress state of soil, which are determined by experiments.

Figure 5 shows the comparison between the predicted permeability coefficient $k^*$ and the final stable permeability coefficient $k$. The results indicate that the equation (5) provides a good estimate of $k$, usually between 1/2 and 2 times the measured value. Therefore, when the loess is compressed, equation (5) is suitable for predicting the permeability coefficient of saturated remolded loess.

4. Conclusion
(1) Triaxial permeability test on saturated remolded loess shows that permeability coefficient decreases with the increase of the permeability time, and stabilizes finally.

(2) A concept of the average permeability coefficient ratio is given and used to analyze the effect of confining pressure on the permeability of loess quantitatively. The results show that the average permeability coefficient ratio decreases and then increase as confining pressure increases.

(3) A mathematic model is derived for saturated remolded loess permeability to better predict the permeability coefficient of loess under different confining pressures.

Acknowledgements
The authors wish to acknowledge the financial support provided by the National Natural Science Foundation of China (NO.51879212), key research and development program of Shaanxi Province (2019KWZ-09) and Natural Science Foundation of Shaanxi Province (2020JQ-988).
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