# A NEW METHOD FOR TESTING THE ANTI-PERMEABILITY STRENGTH OF CLAY FAILURE UNDER A HIGH WATER PRESSURE

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clay failure; seepage deformation; anti-permeability strength; high water pressure

**Abstract**

*It is difficult to judge the failure of clay seepage under a high water pressure.This paper presents a new method to assess clay failure based on the anti-permeability strength, which is the critical water pressure to destroy the clay. An experiment is designed to test the value that avoids the problem of the time-consuming, traditional method to test clay seepage deformation. The experimental system and the process of testing are introduced in this paper. With a self-designed experimental system and method, 18 groups of sample were tested. The results show that the clay thickness and the seepage paths influence the anti-permeability strength. It also indicates that water infiltrates into the clay under the condition that its pressure exceeds a minimum value ($P_0$).*

## 1 INTRODUCTION

Clay is an important structural material to reduce hydraulic conductivity and can be used widely for liners and caps in many projects. It is usually safe to use as an anti-seepage material, but some cases of clay failure have occurred. At present, the research on clay failure concentrates on the hydraulic conductivity ($K$) and the surface erosion. The stability of clay projects is usually judged by the value of $K$ [1-6]. $K$ is a parameter for which the appropriate values are difficult to obtain with good accuracy due to a large pore system [7-8], the effect of the measuring scale [9], the condition including freezing-thawing and drying-wetting [10], overlying soil [1], chemical composition [11], water content [12], etc. The $K$ values measured with an oedometer are lower than those in a triaxial test and vary a great deal with the applied pressure [10], and reduce with an increasing density of the sample [6].

Surface erosion is mainly a form of clay failure. In nature, clay erosion accompanies the evolution of landforms. Couper [13] demonstrated how the surface processes vary with the silt–clay content of river-bank soil and how to consider this variation in the context of erosion observed in the field. Lévy [14] discussed how erosion and landslides are related to valley development. Lamelas [15] shares some of the characteristics of previous models, including the erosion of bare clay surfaces by wave-generated, bottom shear stresses and of mobile, sediment-covered surfaces by abrasion. Another model demonstrates that bluff height, debris mobility, wave undercutting, and groundwater levels are key factors in determining the clay stability of coastal bluffs [16]. In addition, clay erosion influences cultivation. Clay particles can be eroded from the plough layer and transported both laterally and vertically, through pores and cracks into the backfill, and then directly to drain pipes [17]. Messing [9] carried out an in-situ experiment to quantify the effect of a plough on the displacement of soil down aslope. Its result shows that the clay soil removed from the top of the plot is much greater than that estimated for the surface-water erosion. Mukonen [18] advises improving the soil structure and avoiding the disruption of stabilized aggregates in order to prevent erosion in an agriculture field.

However, clay failure includes some forms, except surface erosion, one of which is internal erosion under a high water pressure. Though a dam elevates the level of the water and produces high pressures, the dam core is often made of clay so as to prevent any seepage. However, this has potential risks [19-22]. Previous research on the issue of a clay core is mainly concerned with the material character [23-25], stability [26], testing pressure [27], contact boundary [28], stress strength [29], erosion and permeability [30-31], and monitoring [32]. The process of internal clay erosion, however, is known to contribute to dam failure during high water pressure.The high pressure can lead to an excessive ingress of water into the clay layer, ending in breaching and failure. But very little information is known about internal erosion and how to quantitatively evaluate it. There are no established methods to solve the problem.

The seepage-failure criterion is usually the critical hydraulic gradient. But it is difficult to judge the clay seepage failure, because it has been proved by laboratory soil tests that the seepage deformation of clay is nonlinear. So the critical hydraulic gradient remains unfitted.

The time for that water to penetrate into the clay is the seepage-failure criterion of the clay in this study. Generally, the coefficient of permeability of the clay is less than $10^{-6}$cm/s. Based on the equation of Darcy's law of $V=KI$, it shows $V$ is less than $10^{-3}$cm/s when $I$=1000, and it means that water takes at least 1000sec to penetrate a 1-cm thickness of clay under the condition of $K=10^{-6}$cm/s. It represents a clay failure that the water takes a long time to penetrate normally into the clay. That is to say, the clay structure is a failure when water takes seconds or minutes to penetrate into the clay. The penetrating time is related to water pressure, such that the higher the water pressure, the quicker the water penetrates into the clay. By increasing the water pressure, when water penetrates through the clay at the bottom in seconds or in minutes, the pressure is critical, which is the anti-permeability strength. This study regards the time as the critical condition to judge the clay's failure and introduces a quick method to test its value quantitatively.

## 2 EXPERIMENTAL APPARATUS AND METHOD

### 2.1 Experimental apparatus

The experimental apparatus (Fig.1) is designed to test the anti-permeability strength of clay under a high water pressure. The system (Fig.2) consists of a triaxial instrument, a water pipe, valves, and a sample pot. The confining pressure of the triaxial instrument is chosen to support a high water pressure. The instrument is a Model TCK-1 Triaxial Test Controlled Apparatus, which is made by the Nanjing Soil Instrument factory, one of the earliest and largest enterprises specializing in the production of geotechnical engineering laboratory instruments in China. It performs very well in a high-pressure cell composed of a confining chamber (confining pressure up to 2.5 MPa), and is convenient for reading the value via a digital display.

The water conduit connects the triaxial instrument to the sample pot. The water pressure is transmitted along the water conduit from the confining chamber to the soil

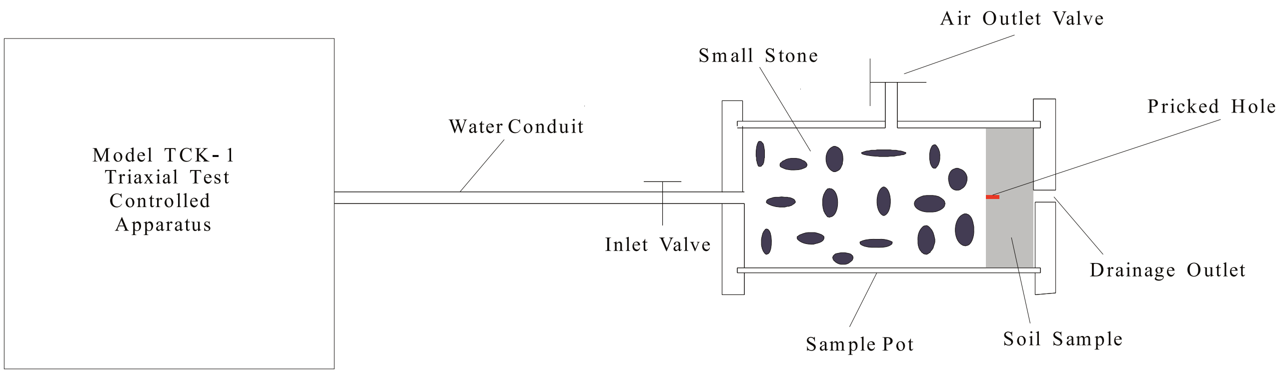


**Figure 1.** Schematic diagram of the experimental apparatus.


**Figure 2**. Testing equipment.

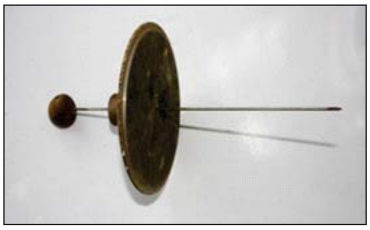

**Figure 3**. Pricking device.


**Figure 4**. Pricked hole.

sample. In order to regulate effectively the water pressure, it installs the inlet valve to control the transmission of pressure by opening or closing the valve.

The sample pot consists of a steel cover, a plastic pipe (diameter 91mm) and rubber packing. They work via a screw. At the top of the plastic pipe, an air outlet valve is fixed to release the air in the water conduit and the sample pot when injecting water into the test equipment. The center tail of the sample pot produces a hole, with a diameter of 10mm, to observe whether the water seeps and the particle is out.

It is only under sealed conditions that the triaxial instrument can support the confining pressure of the water. In the design system, the clay sample at the end of the testing system is most likely opening, but it is not for two reasons. Clay can stop the water loss for the hardly impermeable character. Air is removed in the whole process of the testing program. There is no water and air loss, so it is impossible to release the water pressure unless the clay fails.

### 2.2 Experimental Procedures

In this study, the procedure for the experiment has seven steps, as follows:

a) Sample preparation. The sample is placed in the sample pot, and the contact surfaces are smeared with Vaseline to prevent water or air leakage.
b) Hole piercing.The conical-headed piercing device (20 cm long; 1.5 mm diameter) (Fig. 3) is used to pierce a hole in the center of the sample (Fig. 4). This allows the water to flow, just as water seeps naturally via weaknesses in a subterranean environment.
c) Installation. Following the approach shown in Fig. 1 and the described method, the installation is tested to ensure functionality.
d) *Saturation*. The sample is saturated using a standard vacuum-pump method.
e) Air purging. Firstly, open the inlet and exhaust valve of the sample pot. Secondly, fill with water until the air is completely purged from the test equipment. Finally, close the valve.
f) Increasing water pressure. Rotate the knob controlling the confining pressure at a constant velocity to increase the water pressure (1KPa/s). The water pressure is up to 1 MPa in a few minutes. It is important to be careful as this step is the key to accomplishing the test successfully.
h) Observation and recording. With increasing pressure, observe the phenomenon of water seepage, such as the permeating capacity of the water and the water's turbidity, bubbles, and the flowing particle, and record the corresponding pressure value, crucially.

## 3 JUDGING THE CONDITION OF ANTI-PERMEABILITY STRENGTH

The water pressure provided by the confining chamber of the Model TCK-1 Triaxial Test Controlled Apparatus increases quickly (1 KPa/s), even if the knob is rotated slowly. It works on clay and enlarges the pressure difference between the pores that results in the pores expanding and the structure of the clay particle changes until failure. It has the minimum water pressure that results in the clay's failure, which is judged by the clay particle flows or the coefficient of permeability becomes larger. The former is difficult to observe. The latter appears when water seeps through a certain thickness of clay in a short time as the clay has a low coefficient of permeability (<$10^{-9}$m/s) and an impermeable layer. Fig.5 shows the condition for judging the clay's failure by a variation of the permeability coefficient. In addition, the water pressure is in a closed environment. Once it is destroyed, the water pressure decreases to zero. As the sample is a part of the testing system, that it fails results in the water pressure reducing at the original constant speed of the increasing pressure. The pressure at the time when the water pressure starts to decrease in testing process is the anti-permeability strength.

## 4 MATERIAL TESTED

The specimens tested in this study come from the industrial park of Guilin, China, N 25°13´17.51″, E 110°14´31.50″. Its natural physical property given in Table 1 is tested by the soil laboratory of the Institute of Karst Geology. The clay deposited during the Quaternary is characterized by a hard plastic shape, a block structure, and a high porosity.The average number of the standard penetration test is 9 on this layer, with a thickness of 7m. The water level lies at adepth of 3–4m. As the clay lying water level is weak compared to the other layer, the testing program utilizes the clay layer at a depth of 3.5 meters in order to achieve its purpose. Actually, the sample of undisturbed clay is unsuitable for testing due to the high porosity that results in a deceasing water pressure. It compresses the clay to improve the tested sample. The water content ($w$), the dry density ($\rho_d$), and the void ratio ($e$) of the compacted sample are 31.27%, 1.635g/$m^3$ and 0.671, respectively.


**Figure 5**. The condition of judging clay failure.

## 5 RESULTS

Table 2 shows the testing results for the18 experiments with horizontal and vertical types, 1.0, 1.5, 2.0 and 2.5cm

**Table 2**. Testing result of anti-permeability strength.

| Sample No. | Seepage type | Thick-ness/cm | Anti-permeability strength/KPa | Average value/KPa |
|---|---|---|---|---|
| Y1 | Horizon | 1.0 | 62 | 64.3 |
| Y2 | | | 68 | |
| Y3 | | | 63 | |
| Y4 | | 1.5 | 73 | 68.0 |
| Y5 | | | 66 | |
| Y6 | | | 65 | |
| Y7 | | 2.0 | 79 | 79.7 |
| Y8 | | | 85 | |
| Y9 | | | 75 | |
| Y10 | | 2.5 | 72 | 80.0 |
| Y11 | | | 86 | |
| Y12 | | | 82 | |
| Y13 | Verticality | 1.5 | 85 | 85.0 |
| Y14 | | | 92 | |
| Y15 | | | 78 | |
| Y16 | | 2.0 | 87 | 90.7 |
| Y17 | | | 90 | |
| Y18 | | | 95 | |

**Table 1**. Physical property of original clay.

| $w$ % | $\rho$ kg/$m^3$ | $\rho_d$ kg/$m^3$ | $Gs$ kg/$m^3$ | $e$ | $n$ % | $Sr$ % | $W_L$ % | $W_P$ % | $I_P$ | $I_L$ | $C$ MPa | $\Phi$° | $Es$ MPa |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36.1 | 1810 | 1330 | 2740 | 1.064 | 51.6 | 93.0 | 48.0 | 28.6 | 19.4 | 0.38 | 0.050 | 19.3 | 7.22 |

of thickness. All the tested samples were pricked with a 0.5-cm-deep hole (the red shown in Fig.1) at the center with a pricking deviceto lead the infiltrating way, for the hole is the weakest area that is easily permeated.The testing results show that the seepage types and the sample thickness influence the anti-permeability strength.

The anti-permeability strength is increasing with thickness in the horizontal test type (Fig.6) as well as in the vertical test type (Fig.7). The relationship liner in Fig.6 is matched well with the average value for $R^2$=0.8891. It does not start from the original point, for the function has aconstant (52.467) as the initial pressure ($P_0$) caused by some factors. One factor is the bonding water film around the clay grains. The water film prevents the water from permeating into the internal channel. Thus, the initial pressure reflects the resistance of the water film. When the water pressure over comes the resistance, the water permeates into the clay. The other factor is the particle force, including the friction, the molecular gravity, and the electrostatic force. Clay has a strong particle force to prevent the water from permeating strongly, which is why clay has a lower permeability. Water should exceed the particle force firstly, and then permeate into the clay. Therefore, $P_0$ is the minimum pressure to make the water infiltrate into the clay.

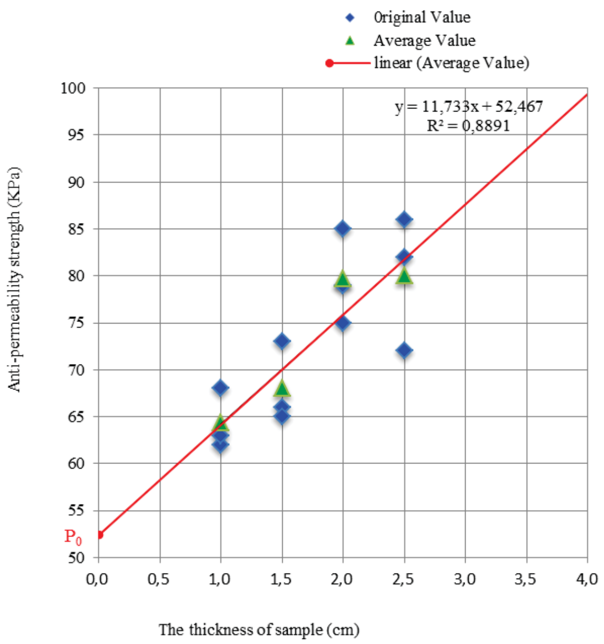


**Figure 6**. Anti-permeability strength of different thicknesses with the horizontal test type.

The anti-permeability strength varies with different thicknesses (Fig.7). In nature, the seepage deformation of the clay varies. The horizontal and vertical types that are common are stimulated in this paper. The vertical type only chooses the downward route. Compared to the strength of the horizontal type (Table 2), the vertical average strengths of the 1.5 and 2.0 cm samples are increased by 25%, and 13.8%, respectively. They are not the same because of the different $P_0$ caused by the different resistances. The resistance comes from the gravity. In the downward direction, the gravity promotes water seepage. But, the gravity resists water seepage in the horizontal type. It can be predicted that the strength of the downward direction is less than the horizontal type, as its resistance to gravity is small.

The critical hydraulic gradient ($i=H/L$, Fig.8) is nonlinear based on the results data. It indicates that the water seeping in clay media exhibits non-Darcian flow behavior, which is the same result as other researchers [33-36]. So the critical hydraulic gradient does not fit to judge

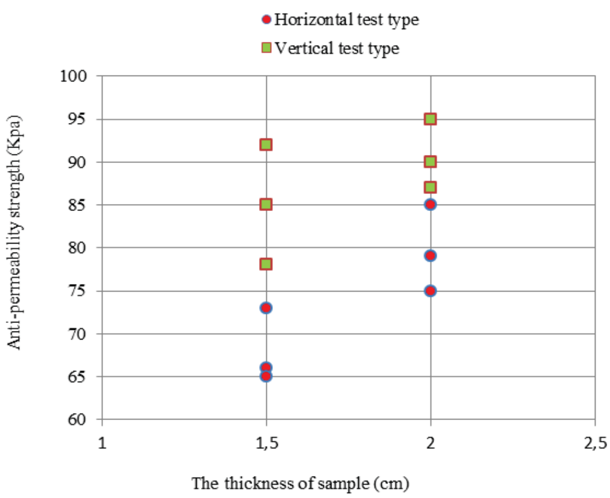


**Figure 7**. Anti-permeability strength of different thickness.

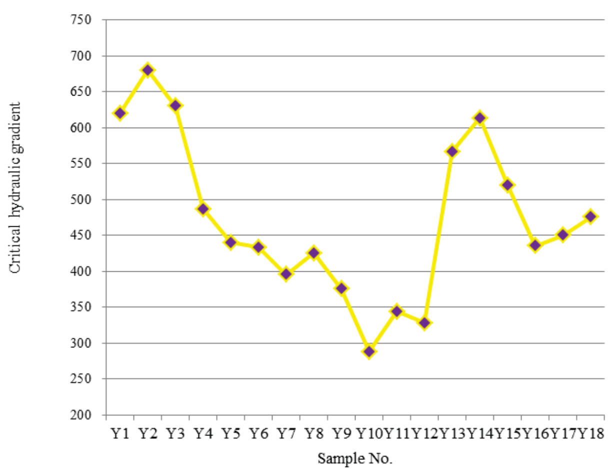


**Figure 8**. Critical hydraulic gradient.

the clay failure. There are four factors that explain the problem, as follows: a) the pores of the internal clay are very small, which results in a strong capillary force that influences the effect of the water head; b) in the process of clay-seepage deformation, the water pressure drives the water to infiltrate into the clay while it compresses the sample that decreases the porosity and changes the structure of the sample; c) the influence of the bonding water film and the particle force was mentioned above; d) the distribution of the effect stress caused by the water pressure is heterogeneous, and it is unsuitable to apply the theory of Darcy's Law in this case.

The water pressure makes the clay fail at its weakness point, not the whole, and the hydraulic gradient is the volume force. Therefore, it is difficult to obtain the effect value that the hydraulic gradient should not be applied to all the samples.

## 6 DISCUSSION

Water seepage in clay media is governed by Richards' equation [37], with the proportionality factor termed the hydraulic conductivity (*K*). It is both difficult and time consuming to measure the functional relationship between *K* and the soil water-pressure head (*H*) [7, 8, 38]. Experimental results indicate that the critical hydraulic gradient is not suitable directly to judge clay failure. The main reason is that the traditional form of Darcy's law is not appropriate for describing water-flow processes in clay media, because the observed relationship between the water flux and the hydraulic gradient can be very non-linear [39]. The non-Darcian flow behaviors in low-permeability media were also investigated by Klausner [40], Alabi [41, 42], while the complexity of field-scale water flow in a clay formation was discussed in [43].

Clay failure depends not only on the hydraulic gradient, but on the friction, electrostatic force, molecular attraction and capillary water pressure between the pores. The critical hydraulic gradient described the relation between the seepage force and gravity, and does not reflect the complex distribution of stress caused by the water pressure [44]. The physical indicators of clay, such as the permeability coefficient, the critical hydraulic gradient, etc., changes while the clay is compressed and the degree of consolidation increases under a high water pressure [45]. Therefore, it is inappropriate to simply consider that the clay failure is determined by the hydraulic gradient.

In this paper, the anti-permeability strength was applied to judge the clay failure under a high water pressure. Compared to the hydraulic gradient, it comprehensively reflects the mechanical properties of clay seepage for it responds to the influence of structure, compression, particle force, etc. It makes up for the disadvantage of the traditional measure, to some extent. Moreover, the values of the experimental results are between 20 and 80 KPa, which is equal to the 2-8m of water head that is common in Nature. Consequently, it is effective and positive to judge clay failure by its anti-permeability strength.

Although the method is not perfect, it gives a new view and a quick way to assess the risk of clay failure under a high water pressure. The experimental apparatus is easy to install in most geotechnical laboratories. Experimentalists can master the testing process quickly. The water pressure is up to hundreds of kilopascal (KPa) in minutes using this system. That makes up for the deficiency of the traditional method to test clay-seepage deformation. It is significant to apply the method of testing anti-aging strength to assess the stability of a dam's foundation made with clay, the probability of reservoir leakage, the susceptibility of clay cave collapse in a Karst region, the pollution risk in a reservoir area due to leakage, etc.

However, the mechanism of anti-permeability strength needs to be researched and the correlation between the strength and the sample size, including the ratio of the height to the diameter, the size of the cross-sectional area, the porosity, the saturation level, etc., should be explored further.

## 7 CONCLUSION

The experimental apparatus and a quick method are designed carefully to test the anti-permeability strength of clay under a high water pressure in this study. Model TCK-1 Triaxial Test Controlled Apparatus providing a high water pressure in minutes in the system avoids the time-consuming problem, which is the weakness of the traditional method to test clay-seepage deformation. The method gives an effective new view to assess the risk of clay failure under a high water pressure. A total of 18 groups of samples were tested with the self-design test equipment and test method. It interprets the relationship between the anti-permeability strength and the clay thickness and seepage ways. The results show that: a) the anti-permeability strength is increasing with the thickness; b), it exists at the minimum pressure ($P_0$) to make water infiltrate into the clay; c), compared the horizontal type, the vertical average strength of the 1.5 and 2.0cm samples are increased by 25%and 13.8%, respectively.

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