ISSN:2790-1688 DOI: 10.56028/aetr.4.1.154.2023

A Method for In-Situ Permeability Testing of Loose Porous Media Based on Vacuum Extraction

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Abstract. The permeability of loosely porous media is difficult to test. A vacuum extraction based in-situ permeability test for loose porous media has been proposed. The calculation follows from the typical Darcy's law. A mathematical computational model of in situ permeability testing based on pressure decay curves has been developed. The effect of the depth of the return packing on the permeability test is analysed and the permeability of the porous media is obtained to verify the validity of the calculated method.

Keywords: vacuum extraction; loose porous medium; permeability; in-situ test.

1. Introduction

The air permeability represents the ability of air to flow through the medium and is defined as the velocity of air penetration in the medium when the pressure gradient is one. Sand, soil, coal dust, grains, and other types of granular accumulation can be considered as continuous porous media. In-situ permeability is a basic meaning of soil and water conservation, heavy metal pollution migration, the optimization of fluidized bed, the location of the oil bank and the food strategy reserve. Currently, the permeability of porous media is tested in the laboratory. The loose porous medium was sampled by a tube, and the single phase fluid (air or liquid) is introduced at one end of the tube, which is used to form the flow in the material layer, the steady state flow and the pressure was tested, and the permeability in the porous medium can be calculated[1, 2]. However, because of the state damage of the loose medium, the test results are significantly affected by the sample quality, the test result is difficult to accurately represent the gas permeability of the loose formation.

In the in-situ permeability test, the method of in-situ pressure water test was carried out by Mohammad, and the permeability data of different depths was obtained[3-5]. The method of sealing holes at both ends in-situ permeability test method was proposed by Niu, which can be applied to the soil or the solid rock formation[6-8]. Based on the classical theory of Darcy experiments, Sun designed in-situ test equipment. The equipment of the test was designed based on the theory of the classic Darcy test comprising water infiltration system, water supply system and measuring system[9]. During the experiment, the soil was submerged by water, with a constant head maintained by a Marriott tube. These methods are difficult to conduct effective sealing and permeability data. In addition, there are instruments that perform in-situ tests on the surface of the material. The permeability of the surrounding rock can be calculated by measuring the pressure variation and the internal cavity parameters. The method is mainly applied to the laboratory or thin objects, but it is difficult to apply to a certain depth[10-12]. Therefore, a new test of permeability for loose porous media such as sand, soil, coal dust, and grains is needed, in particular, a method to achieve particle accumulation type permeability using spherical suction cavities, vacuum pumps, pressure sensors, and other devices.

In Section 2, the principle of the in-situ test of permeability of loose porous media is described. The in-situ percolation test procedure is performed in Section 3, which focuses on the in-situ percolation test experiments and verifies the effectiveness of the proposed method.

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2. Test principle

The liquid is used as a percolating medium and the permeability is calculated using the Darcy formula.

$$K_1 = \frac{Q_1 \mu_1 l}{A(P_{in} - P_{out})} \tag{1}$$

where K1 is the permeability, A is the cross section of the core, Pin is the inlet pressure , Pout is the outlet fluid pressure, μ_1 is the liquid dynamic viscosity,Q1 is the liquid flow and l is the body length. If the gas is used as an osmotic medium, the compressibility of the gas needs to be taken into account and the permeability calculation becomes the modified derivative form of equation 1.

$$K_g = -\frac{Q_0 P_0 \mu}{A} \frac{dl}{pdp} \tag{2}$$

Where P0 is the standard atmosphere pressure（1.015×105 pa）, P2 is the inflatable pressure, P1 is the pressure before inflation, Q0 is the gas flow under the standard pressure of the standard pressure P0, μ is the fluid dynamic viscosity, under room temperature the fluid dynamic viscosity is 1.88×10-5pa.s.

The idea of the in-situ permeability test is to construct a breathable spherical cavity in a loose medium with a gas pressure in the cavity smaller than the local atmospheric pressure. The gas permeability of the surrounding medium is calculated by testing the velocity and pressure of the vacuum pump against the relative pressure.

For loose porous media, based on the flow of porous media in 1D spherical shells, the flow of porous media in spherical cavities is

$$Q = \frac{-4\pi r^2 p_r k}{u} \frac{dp_r}{dr} \tag{3}$$

where Q is the amount of gas that flows through the medium in the unit time (Pa·m3/s), r is the distance between any point in the medium and the cavity center(m), pr is the gas pressure of the medium at r (Pa), k is the permeability of the medium (m2).

The boundary conditions r=r1, pr=p and r=r2, pr=pa are introduced. The equation(3) becomes

$$Q = \frac{2\pi k(p_a^2 - p^2)}{\mu\left(\frac{1}{r_1} - \frac{1}{r_2}\right)} \tag{4}$$

where p is the gas pressure in the spherical cavity(Pa), pa is the local atmosphere pressure(Pa), r1 is the spherical cavity radius (m), r2 is the radius of the gas exhaust boundary (m).

In the steady state, the gas flow into the vacuum pump is balanced by the gas flow through the porous medium.

$$Q = sp_e = C\Delta p \tag{5}$$

where s is the inlet pumping speed of the vacuum pump (m3/s), pe is the vacuum pump inlet pressure (Pa), C is the equivalent flow (m3/s).

The spherical cavity radius r1 air power viscosity μ and the local atmosphere pressure pa are known parameters, and the gas boundary radius r2 is the minimum distance between the spherical cavity and the porous medium freedom surface. The inlet pump velocity, the pressure difference between the spherical cavity and the atmosphere, and the inlet pressure of the vacuum pump can be measured directly. When the pressure loss in the windpipe is small, the pe value is almost equal to the local atmosphere. When the pressure loss in the trachea is large, the pe will be significantly lower than in the local atmosphere.

Since the equivalent flow conductivity is the ratio of the gas to the pressure difference, the relationship between the equivalent flow conductivity and the average permeability of porous media is

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$$k = \frac{C\mu\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}{2\pi\left(p_a + p\right)} \tag{6}$$

3. Test process

First, the porous medium is excavated and a spherical cavity of radius r1 is filled into the porous medium with a placement depth of r2. The in-situ permeability test setup is connected as shown in figure 1. Breathing spherical cavities can be machined from metal sintering material, and the number of air holes should not be too small. Spherical cavities can also be made of thin-walled metal, the surface of which can be perforated uniformly and then fixed in the granular medium using a gauze uniformity to prevent dust particles from entering the cavity during extraction.

The low-voltage end of the differential pressure sensor is exposed to air, and the high-voltage side is connected to a spherical cavity. The vacuum pump is open to the spherical cavity and the control valve stabilizes the pressure difference between the spherical cavity and the local atmosphere at 1 kPa. The velocity and pressure of the vacuum pump inlet are obtained, and the equivalent flow conductivity and permeability of the porous medium are calculated according to equation(6).

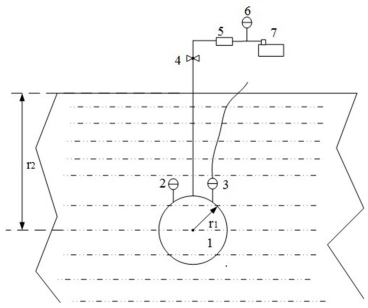

Figure 1. Schematic of the in-situ permeability test. 1-spherical cavity, 2, 6-absolute pressure sensor, 3-differential pressure sensor, 4-regulating valve ,5-flow meter, 7-vacuum pump

In northwest China, natural sand dunes were selected and air cavities were performed in a sand medium. Pressure variability and distribution properties of the media have been studied. The pressure of the cavity and the atmosphere are monitored. In the experiment, the negative end of the pressure sensor is exposed to the cavity and the positive end is exposed to the air guard. The sampling frequency is 10Hz. A photo of the experiment site is shown in figure 2.

Figure 2. Sand cavity extraction experiment

The cavity radius r1 is 150 mm, and the maximum buried depth r2 in the center of the cavity is 1.1 m. The cavity is filled with sand. The extreme pressure of the cavity is shown in figure 3 for different backfilling lengths of 0.3m, 0.6m, 0.8m, 1.1m. It can be seen that the cavity can be 340Pa below the atmosphere at a depth of 1.1 m. As the depth of the backfill increases, the polar differential pressure decreases. When the depth of the return filling is five times the cavity diameter, the polar pressure is almost the same.

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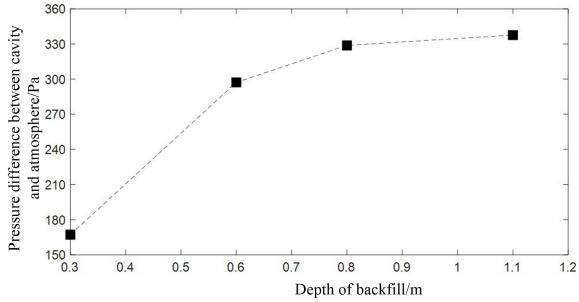

Figure 3. Maximum pressure of the cavity at different backfilling depths

Figure 4 shows a single suction pressure curve for a blank chamber with different backfill depths. As the gas resistance of sand is poor, the pumping and holding time is very short (less than 5s).

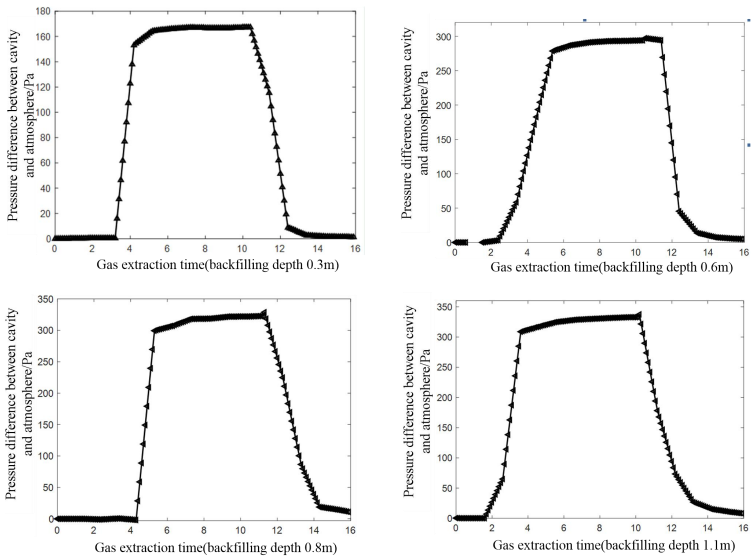

Figure 4. Cavity suction pressure curves for blank cavities at different backfilling depths

At the maximum backfilling depth of 1.1m, the experiment monitored the pressure distribution along the distance from the cavity. The monitored data is shown in table 1. Dm is the distance between the medium and the cavity center (m), PR is the relative pressure between the test point and the atmosphere. As can be seen, the relative pressure of the test points decreases with the distance.

Table1. Pressure profile of the medium along the path of the state of the state

D_m	0	0.5	0.6	1.0	1.4	2.5
P_R	337.6	78.5	69.0	21.0	18.5	6.0

The one-dimensional flow model of the spherical cavity in the uniform porous medium is simplified, and the distribution of the stroke pressure is calculated according to equation(7). The pumping boundary radius is 40 times the cavity radius (3m), and the local atmosphere is 90kPa. In the steady-state flow regime, the pressure profile of the surrounding rock can be obtained based on the continuous equation dQ/dr=0.

$$p_r^2 = p^2 + \left(p_0^2 - p^2\right)\frac{\frac{1}{r_1} - \frac{1}{r}}{\frac{1}{r_1} - \frac{1}{r_2}} \tag{7}$$

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where p is the cavity absolute pressure(Pa), p0 is the local atmosphere pressure(pumping boundary pressure, Pa), r1 is empty cavity radius(m), r2 is pumping boundary radius(m).

Comparison of the theoretical calculated curves with the measured values in figure 5 shows that the trends of the two variations are essentially the same. The negative pressure of the test values is smaller than the theoretical calculations at the 0.5m and 0.6m positions. There are three possible reasons for this, one is that the in-situ medium density is reduced due to artificial backfilling. The second is the loss of pressure by the gas pipe. The pressure loss due to the shorter tube is negligible. The third is a certain kinetic pressure due to the air velocity at the test point, which makes the negative pressure value smaller.

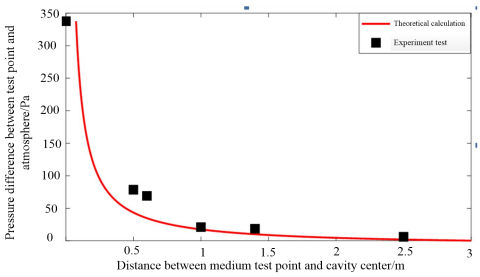

Figure 5. Comparison of theoretical calculations and experimental pressure distribution values

Figure 6 shows the pressure difference as a function of time at 0.5 m and 0.6 m away from the cavity center. It can be seen that the pressure of the cavity and the medium change synchronously. The medium pressure is also stable when the cavity is pumped to limit the pressure.

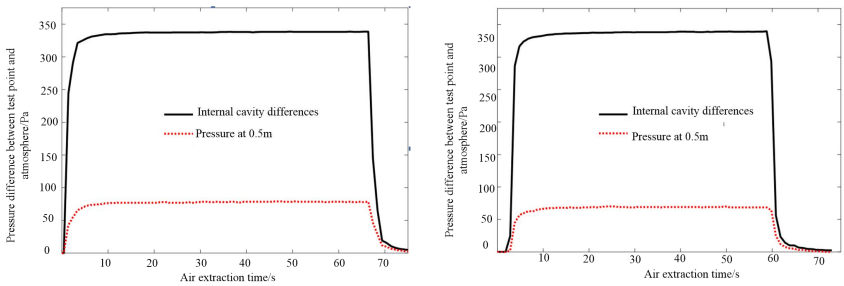

Figure 6. Time-dependent pressure differences at 0.5 m and 0.6 m from the cavity center

In the experiment, the pressure of the pump was monitored and the effective pump speed at the cavity exit was 1.24L/s and the equivalent flow rate of the cavity was 330L/s. The gas boundary radius of r2 is 3m, and the air dynamic viscosity is 1.81×10-5Pa·s. Then the average permeability of sand around the cavity is 3.35×10-11m2.

4. Conclusion

In this paper, we study the effect of the back-filling region on the cavity permeability test. Using a micro-negative spherical cavity, the loose porous medium particles are not displaced by the gas flow, which can reflect in-situ parameters of the permeability of the porous medium.

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