Study on seepage characteristics of inclined wall dam after heavy drought

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Abstract: For seepage of the dam slope with cracks after drought, there are two methods to study including the physical model test and numerical calculation. However, the physical model test can not visualize the seepage field in the dam body intuitively, and the mathematical model is not accurate because of the precision of the parameter. So in this paper, combined physical model with mathematical model, the surface crack development on the dam slope and the changes of pore water pressure were studied through the physical model test, and then numerical calculation was carried out to analyze the internal seepage of the dam body. The results showed that cracks were more likely to develop at middle of the upstream dam slope and dam heel, and cracks for different degrees appeared at different parts of the dam slope after drought. The development of cracks provided a preferential permeable channel which caused that the area near the crack was easily to become saturated. The saturated zone kept expanding leading the infiltration line to be close to the transition layer and the infiltration line was no longer a smooth curve. There were seepage damages and landslide hazards existing with such seepage characteristics, which would threaten the safety of the dam.

1. Introduction

The change and variability of the global climate have increased the frequency and intensity of extreme hydrological events. Influenced by that, the climate change in China has increased dramatically in recent years. According to statistics, from 2009 to 2010, southwest region suffered severe drought since the meteorological record. In the summer of 2013, there was a rare history of high temperature and less rain in most areas of the south of the Yangtze River. In 2014, Henan suffered the worst drought in 63 years. The northern and the midwestern areas suffered a severe drought, resulting in that the water level of multiple reservoirs was close to the dead water level or below the dead water level. The extreme low water level and drying of the reservoir caused the dam to produce a large range of cracks which destroyed the continuity and integrity of the impervious body, and it would endanger the seepage safety of the dam [¹²].

At present, the methods of studying on seepage in cracked soil include physical model test and numerical model calculation. By changing the depth of crack, the height of water in the crack and test material, Fan Jianli [³] made a single crack test model in the self designed test equipment to study the relationship between infiltration volume and these experimental conditions, and then got the relationship between the amount of infiltration and the height of water level, material permeability coefficient and crack depth. Yang Hua [⁴] designed a new modular soil permeability equipment and an
anti steamed double loop infiltrating instrument which was easy to be installed and fixed to study the seepage characteristics of cracked loess. The results showed that the existence of cracks provided the dominant channel for water flow, and the infiltration rate in cracked soils was obviously higher than that in homogeneous soils. Luo Jipeng's [5] seepage test was carried out under different normal loads on artificial fractures through a fractured radiant flow test device, and he found that the seepage flow under the different normal stress was approximately linear with the infiltration head, which showed that the motion characteristics of the fissure water in the test were in accordance with Darcy's law. In the aspect of the numerical simulation, Huang Zhaoqin [6] established the discrete fractured model, based on the concept of discrete fracture. She elaborated the basic principle of discrete fracture model and its two-phase flow mathematical model, and established the finite element numerical calculation scheme of the model based on Galerkin weighted residual method. A permeability coefficient tensor correction method was proposed by Gao Xiao [7] under the framework of equivalent continuous medium model. Based on the flow equivalent principle, the permeability coefficient tensor matrix of the correction element was derived. The finite element analysis software was applied to calculate the seepage field and the results were consistent with the numerical analysis results of the cracks. Through the analysis and inference of the critical seepage phenomenon of the gas liquid two phase fluid in the crack, Yang Dong [8] established a mathematical model of the random mixed seepage to describe this phenomenon. The model was applied to simulate the probability distribution range of critical seepage phenomena, the microscopic distribution characteristics of gas and water connected clusters and the distribution characteristics of pressure gradient in critical seepage area.

From the existing researches, it could be found that most of the physical model tests were the law of the seepage in the cracked soil, and the accuracy of the test results was questioned by the limitation of the similarity ratio of the test conditions. The numerical simulation was generally based on theoretical deduction to carry out the study of seepage flow in cracked soil, but the process of analysis and the selection of parameters are ideal. Therefore, considering the combination of model test and numerical calculation, taking advantages of each method to study the seepage characteristics of the cracked soils.

2. Physical model test
The purpose of the physical model test was to obtain the progress of the seepage when the soil was exposed to the rainfall after the drought.

2.1. Test Model
The soil samples used in the test were excavated from the upstream dam slope of Zhaopingtai Reservoir in He’nan Province, China, and it mainly consisted of clay (23%) and silt (46.8%), with some sand (18.5%) and gravel (11.7%). The volume water content at the site of the engineering was 31.4%, and the water content of the surface soil was obviously affected by rainfall. By measurement, it was found that the average wet density of the soil was 1.64g/cm³, and the saturated permeability coefficient is 1.69 ×10⁻⁶cm/s. After the soil was retrieved and dried, the particle sieving and the liquid plastic limit were measured. The results of the determination were shown in Table 1 and Table 2.

| Gravel % | Coarse sand % | Medium sand % | Fine sand % | Silt % | Clay % | Effective particle size mm | Inhomogeneity coefficient |
|----------|---------------|----------------|------------|-------|-------|---------------------------|--------------------------|
| 0        | 4.8           | 6.9            | 18.5       | 46.8  | 23    | 0.002                     | 17.5                     |

| Liquid limit% | Plastic limit% | Plastic index |
|---------------|----------------|---------------|
| 30.8          | 17.1           | 13.7          |

The test model was made in proportion to 1:28, and the size of each part was shown in Figure 1.
ensure the good-quality model filling, layered filling was used. To control the height of each layer, the elevation was marked on the outside wall of the tempered glass for reference. However, it was difficult to control the slope of each layer, so after the whole construction was completed, slope shaping was carried out. There are 9 seepage gauges used in this model, as shown in Figure 2. In the test, the seepage gauges and the rain flowmeter were all connected to the automatic data acquisition system. The test was conducted in a home-made environment box (as shown in Figure 3), and the test system could be used to simulate drought and rainfall.

![Figure 1. Test model](image1)

![Figure 2. Embedded position of instrument](image2)

![Figure 3. Model system](image3)

(1-Model of dam, 2-Tempered glass cover, 3-Water pipe, 4-Rain line, 5-Atomization nozzle, 6-Long arc xenon lamp, 7-Fan, 8-Booster pump, 9-Flow meter, 10-Drain hole, 11-Rainfall/Impound valve)

2.2. Test Results
The test process was divided into 3 steps, which were the initial water storage, the simulated drought and the rainfall storage.

In the first step, the water level in front of the dam was up to 1.2m corresponding to the check water level, and was kept unchanged for about 40 hours. Then the water was pumped out to simulate the drought. The xenon lamp and fan would be turned on during the drought. The temperature inside the environment box was not lower than 30℃. After the development of the crack in the dam slope was basically stable, the process of drought stopped. The duration of drought was about 350 hours. In the third step, artificial rainfall was conducted to increase the water level. The variation of the pore water pressure was observed in each period.

![Figure 4. Pore water pressure in the first stage](image)

The variation of pore water pressure in the first stage was shown in Figure 4. The pore water pressure in the front of the blanket was the first to change, and rose slowly at a fast rate. Then the pore water pressure at the back of the blanket changed 6 hours later. In addition to the front of the blanket, pore water pressure at all parts changed at the same time. The water level remained unchanged for 18 hours after the blanket was submerged and this caused the pore water pressure to remain unchanged. Afterwards, the water level rose rapidly, except the the middle part of the inclined wall, pore water pressure at all parts increased. Because of the high displacement potential at the middle of the inclined wall, both the change rate and the amplitude were smaller than other parts. When the test was carried out for 50 hours, the water in front of the dam was pulled out and the water level decreased rapidly, which led to a sudden drop in the pore water pressure in each place.

![Figure 5. Crack development](image)  
![Figure 6. Pore water pressure in the second stage](image)

Development of cracks and changes of pore water pressure in the second stage were shown in Figure 5-Figure 6. In the drying stage, because the water in the I and III area was not completely discharged, the pore pressure at the front of the blanket and sand layer was not close to 0. According to the characteristics of general osmometers, when in a water environment, the working state of the sensor was stable, but when they were in the dry soil, due to the influence of instrument accuracy, the measured values would slightly beat. The situation of data jump of pore water pressure during the drought coincided with the actual engineering phenomenon.
Development of cracks and changes of pore water pressure in the second stage were shown in Figure 7- Figure 8. Because the seepage was unsaturated seepage and the expansion of cracks would make the water flow first choose to pass through the cracks and then infiltrate into the soil pores, the pore water pressure varied little. For the front of the blanket, the degree of drought was not as heavy as that at the inclined wall section. With the change of water level, the pore water pressure varied greatly, and the flow could infiltrate into the soil from the top of the blanket, so the pore water pressure varied greatly in this area. Due to cracks developed at the backend of the blanket and the bottom of the inclined wall were developed, the water flow quickly permeated the cracks during the period of the water storage. At this time, the seepage coefficient of soil was very small, and the water flow in the crack was difficult to enter the soil, so the pore water pressure increased slowly. During the test, several times of rainfall were carried out, and there was a certain time interval between each time. Water leakage would occur when the environment box was subjected to large internal water pressure, and that made the water level in the front of the dam constantly decreased. For the middle of the inclined wall, because of the most developed cracks, the pore water pressure was easier to be affected by the water level. As the rain went on, the accumulation of water at the back of the environment box would increase gradually. The water was then drained and the water level in the sand was reduced. So repeated operation resulted in the fluctuation of pore water pressure in the sand.

The pore water pressure at each part during the two stages of the test was compared (as shown in Table 3).

|                  | Front of the blanket | Back of the blanket | Lower part of the inclined wall | Middle of the inclined wall | Bottom of the sand |
|------------------|----------------------|---------------------|---------------------------------|----------------------------|--------------------|
| Primary water    | 5.2                  | 4.2                 | 4.0                             | 0.7                        | 3.3                |
| storage          |                      |                     |                                 |                            |                    |
| Second water     | 2.3                  | 1.0                 | 0.8                             | 0.5                        | 0.5                |
| storage          |                      |                     |                                 |                            |                    |

3. Numerical Model

3.1. Computational Model

After the extreme drought, crisscross cracks will appeared at the Impervious body. For numerical calculation, according to the actual situation, negligible influence can be ignored for relatively fine cracks, while the larger width of cracks should be considered for seepage. When the effect of the crack is considered, there are two common methods of treatment [10-15]: (a)The method of equivalent permeability coefficient. This method does not consider the existence of the crack alone, and divides it
into a fine element mesh. In this way, the permeability of the crack can be equivalent to the permeability of the fine mesh area, and the permeability coefficient of the crack region is far greater than the permeability coefficient of the surrounding soil. At this time, the water flow on the surface of the soil will take the lead in infiltration through the meshes of the fracture unit, and quickly make the region saturated and then spread to the surrounding soil. (b) The method of taking the sides of a crack as a boundary. In this method, the cracks are analyzed independently, and the sides of the cracks are regarded as the boundary of the dam slope. When the calculation is carried out, the cracks are removed from the body of the dam firstly and then the mesh is divided, so that the cracks become a part of the boundary. In this paper, the first treatment method is used for cracks with larger opening.

According to the drought in 2014 in He’nan Province, combined with the results of the physical test, the actual situation of the cracks in Zhaopingtai Reservoir is considered. In the calculation, the cracks are considered to be located at the junction of the blanket and the inclined wall, the lower, the middle and upper part of the inclined wall. The parameters of the model material are in accordance with the soil in the test. Considering that the cracked block is not a complete soil or hole, but the soil and pore are interlaced, the permeability coefficient of the cracked block is set to 0.01m/s.

3.2. Calculation Condition
The design of the working condition is similar to the test process. In the condition of heavy rainfall, the upstream water level rises rapidly. According to the regulations of the meteorological department, when the rainfall is above 140mm, it can be seen as a heavy rainstorm, and based on that, the numerical calculation of rainfall is conducted. By conversion, 140mm/12h=3.2×10^{-6}m/s. The permeability coefficient of the soil is 1.69×10^{-6}cm/s which is less than rainfall intensity, so 1.69×10^{-6}cm/s is selected as the infiltration rate of water. However, for unsaturated soil, the rainfall infiltration is actually controlled by the water supply intensity and the soil infiltration rate. At the initial stage of infiltration, soil moisture content is relatively low, and water supply intensity is less than soil infiltration rate. Therefore, the actual infiltration rate is the intensity of water supply. In order to determine whether the water supply infiltration or infiltration capacity of the soil to be chosen, it is necessary to know when the infiltration values of the two infiltration modes are equal. Combined with the soil water characteristic curve function and the function of permeability coefficient, it is found that at the blanket, when these two kinds of infiltration are equal, the water content should reach 8%. After the drought, the water content at the blanket is more than 8%, so the infiltration of water is dominated by the self infiltration capacity of the soil. At the dam slope, when these two kinds of infiltration are equal, the water content should reach 13%. After the drought, the water content at the dam slope is about 9%, and it takes about 5 hours of rain to make them equal. Therefore, the water supply intensity is chosen in the first 5 hours, and then the soil permeability plays a leading role for calculation.

3.3. Calculation Results
Seeage situations before the drought, with cracks and with no cracks were analyzed. The runtime was 200 hours, and the results are shown in Figure 9- Figure 11.
According to the calculation results, it could be found that under the condition of cracks, cracks became the infiltration channel of water flow, and the saturated zone was easy to form around cracks. The existence of cracks made the infiltration line in the soil no longer be a smooth curve. As the seepage went on, the infiltration line next to cracks in the inclined wall gradually approached the transition layer. Because of the difference of permeability between the cracked zone and the non-cracked zone, the inclined wall was gradually divided into sections of saturated-unsaturated phase. It not only reduced the impervious performance of the clay inclined wall, but also caused the local landslide on the upstream surface due to the difference of the mechanical parameters between the saturated soil and the unsaturated soil.

4. Conclusion
In view of the special climate phenomenon of strong drought, the physical model test and numerical calculation were conducted to study the difference of the seepage field in the inclined wall dam before and after the drought. It was found that after the drought, cracks in the middle of the dam slope were most developed. The formation of cracks permanently increased the porosity of the soil, changed the permeability of the soil, and permanently weakened the impervious performance of clay blanket and inclined wall. When the water level rose, the saturated zone was easily formed around the cracks, which made the final infiltration line close to the transition material and seriously endangered the safety of the dam.

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