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Discusion on Failure Mechanism of Piping

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Supposing that the layer is consisted of two ideal elastic spheres with different diameters, the permeability coefficient of the layer can be calculated. After piping taking place and small grains being carried away, the permeability coefficient will change. The piping model is made to quantificationally calculate the permeability coefficient and hydraulic head of any point. The model explains the causes of piping and the development of concentrated passage, and it provides theoretical basis for prevention of dam piping.

1. Introduction

Dam break is mostly caused by permeability deformation, and slope sliding accidents are also caused by seepage, which are in the references of Evans et al.(2000), Liu (2012), Zhao et al. (2015), and Fread (1996). The dam of Yangtze River bursted in 1998, which were mostly caused by permeability deformation such as piping. The study of piping has been studied by many former, such as the literatures of Awal et al. (2012), Awal et al. (2008), and Meyer et al. (1994). But the damage cause of the layer which is caused by piping has been done little. The only way is to study the law of the grains moving in the layer after piping taking place. So the damage to the around layer which is caused by the piping can be studied further, and then reinforcing engineering for the dam can be guided.
The mechanism of the seepage passage which is caused by piping has been studied qualitatively, and has been validated by Chen (2000). After the piping taking place, the groundwater well theory can be introduced to study the initial seepage field during piping. Piping can be approximately regarded as artesian well, and the river can be looked as half no-boundary with fixed water level. Steady flow theory or unsteady flow theory can be applied to study the distribution and the variety of the seepage field during the early period of piping. The complex interaction of the seepage water and soil determines the seepage time, which is a non-linear dynamic problem. The layer is predigested to be consisted of two ideal elastic spheres with different diameters, and the cohesion is ignore. The permeability coefficient can be equivalent as the average permeability coefficient of the layer consisting of two spheres with different diameters. So the variation rules of the permeability coefficient, critical surface, water grads, and so on can be calculated quantificationally after piping taking place.

2. Model of permeability coefficient of the layer after piping taking place

2.1 Permeability coefficient of the layer

The actual layer is very complex, and the layer which may conduce piping is not well sorted. In order to establish the quantitative seepage model, we should start from simple model, and then induce the more complex sorted layer. Supposing the layer is consisted of two spheres with different diameters, and the small particles are all taken out of the big particles, the dam will be damaged because of the side force. We mainly discuss the form of the large particles liable to move while the small particles are carried away.
The permeability coefficient K of the layer which is consisted of two kinds of grains can be shown:

$$K \cdot J = K_1 \cdot J \cdot A_1 + K_2 \cdot J \cdot A_2 \cdot \eta$$

Two sides of the equation can be simplified:

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$$K = K_1 \cdot A_1 + K_2 \cdot A_2 \cdot \eta \tag{1}$$

Where K_1 is the permeability coefficient of the layer consisted of large grains; K_2 is the permeability coefficient of the layer consisted of small grains; A_1 is the area ratio of the large grains to the layer; A_2 is the area ratio of the small grains to the layer. Mao (2003) gave the expression of the permeability coefficient of the layer consisted of one kind of grain.

$$K = \frac{\beta \cdot n^2}{\lambda(1-n)} d^2 \frac{\gamma_w}{\mu} \tag{2}$$

Where β is form coefficient ($\beta=\pi/6$ for sphere); n is porosity; λ is the effect coefficient of of the adjoining grains; d is diameter of the sphere; γ_w is the density of water; μ is coefficient of viscosity of the fluid.
When the porosity of large particles is filled with small particles, permeability coefficient is determined by the area ratio of small particles to the layer. When small particles are all carried away, permeability coefficient is determined by the area ratio of large particles to the layer. So permeability coefficient in any cell in the layer is determined by part of large particles and small particles, shown in Figure 1.

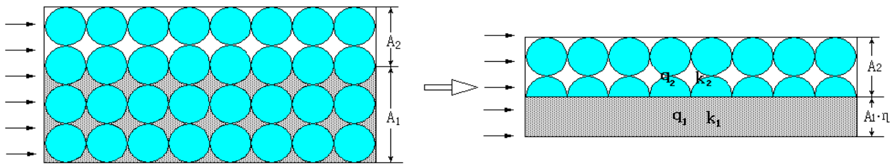


Figure 1: Equivalent permeability coefficient after small grains carried away

When the overlay is penetrated by the hydraulic water after the piping taking place, the static hydraulic pressure releases, water effusing from the piping well. The streamlines and the equipotential lines around the piping well redistribute. We can use the theory about steady flowing of a well in confined aquifer to approximately determine the streamlines. We can regard the piping as artesian well. The length between the artesian well and the replenishment river is *a*, the discharge Q. During the process of piping, the hydraulic head of the replenishment boundary doesn't change. We can replace the recharging boundary with a recharging image well. The river is regarded as recharging source, flow in the early period of the piping can be considered as laminar flow. The y coordination is parallel to the dam, and x coordination is through piping well and perpendicularity to y coordination. By the method of images applied to the well, Liu (2001) expressed the drawdown S at any point (x,y):

$$S = \frac{Q}{2\pi T} \ln \frac{\sqrt{(x+a)^2 + y^2}}{\sqrt{(x-a)^2 + y^2}} \tag{3}$$

Where T is the coefficient of transmissibility.

Let $\frac{(x+a)^2 + y^2}{(x-a)^2 + y^2} = \exp(\frac{4\pi TS}{Q}) = c$, so the following equation can be obtained:

$$(x - \frac{(1+c)a}{1-c})^2 + y^2 = \frac{c^2 a^2}{(1-c)^2} \tag{4}$$

Supposing different values to *S*, we can divide the flow field according to the values of *S*.

First the discharge of the early period of the piping was calculated, and then overall discharge can be assigned to any cell. In the period time of Δt, the permeability coefficient doesn't change, and the permeability coefficient in the cell is constant. We can calculate flow velocity and actual velocity by permeability coefficient, hydraulic gradient and so on. If the flow velocity can carry small particles to move, small particles can be carried out of the cell. Supposing that the capacity of small grains transport relies on velocity in the porous medium, and the volume of the small grains transport from the no.i cell is ΔV_i, from Eq(1) the following equation can be expressed:

$$K = K_1 \times \frac{\Delta V_i \times \Delta t}{\Delta S \times \Delta L \times M} + K_2 \times (1 - \frac{\Delta V_i \times \Delta t}{\Delta S \times \Delta L \times M}) \times \eta \tag{5}$$

Where ΔS is the length of the cell; ΔL is the width of the cell; M is thickness of the layer. The discharge of the piping Q can be obtained according to water level of the river and ground elevation around the piping after piping taking place, and hydraulic loss Δh can be calculated as follows:

$$\Delta h = C \cdot Q^2 \tag{6}$$

Where C is well loss constant, and can be determined by experiment. When water is confused flow, hydraulic loss will be direct ratio to square of discharge.
From $H=H_0-\Delta h$, hydraulic head of the piping well can be calculated, where H_0 is static hydraulic head. We can calculate the initial discharge of the piping.

$$Q = \frac{2\pi K(H_0 - H)M}{\ln(\frac{2a}{r_w})} \tag{7}$$

Where r_w is radius of piping well, M is the thickness of the aquifer.
In the early period of the piping the flow quality through each cell is equality. We take the radial i cells for example, shown in Figure 2. Flow quantity through this cell is q. There is no recharge from the adjoining cells, $q_1=q_2=q$. Lu (2006) and Chen et al. (1999) calculated the hydraulic gradient of the seepage passage in the early period by the image method.

$$J(x,y) = \sqrt{{J_x}^2 + {J_y}^2} = \frac{aQ}{\pi K_0 M}\frac{\sqrt{(a^2+y^2-x^2)^2+4x^2y^2}}{[(x-a)^2+y^2][(x+a)^2+y^2]} \tag{8}$$

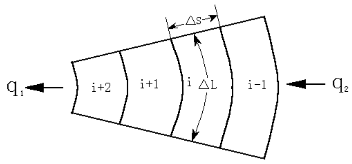


Figure 2: The part of cell

2.2 The permeability coefficient of the layer after piping taking place

After piping taking place, hydraulic gradient near piping well is maximal. The critical hydraulic gradient can be calculated as follows:

$$J_c = (\frac{\gamma_s}{\gamma} - 1)(1-n)\alpha\frac{d}{d_{sk}} \tag{9}$$

Where d is the diameter of the lost particle; d_{sk} is equivalent diameter; γ_s is unit weight of soil grains; γ is unit weight of soil; α is shape coefficient of soil grains. When the velocity reaches starting velocity of the small grains, small grains will move, the starting velocity of small grains can be calculated as follows:

$$BV^2 + MV - N = 0 \tag{10}$$

Where $M = \frac{6Av(1-n)}{d_{sk}}$, $N = \frac{1}{6}(\frac{\gamma_S}{\gamma} - 1)\alpha n^3 g d_s$. For velocity of laminar flow's is small, B=0, so $V = \frac{N}{M}$.
After small grains move, the quality of moving grains in each cell is different. Cell is nearer to the piping well, the more small grains are carried away. We can use the quality model to work out reduced small grains in the cell, and then calculate the permeability coefficient. In Figure 2, considering the no. i cell, in the period of Δt the decrement of small grains in the cell can be calculated as follows:

$$\Delta V_i = V_i - V_{i-1} \tag{11}$$

Where V_t is the volume of small grains carried away from *i* cell, V_{i-1} is the volume of small grains carried into *i* cell.
So we can calculate the small grains decrement in each cell in period of Δt according to flow velocity. From Eq(1) and (2) we also can calculate permeability coefficient in each cell. For the permeability coefficient in each cell has changed, we can't use Eq(7) or Eq(8) to calculate the discharge and hydraulic gradient in next Δt. To calculate the discharge, we should calculate the radial equivalent permeability coefficient, and then sum up each permeability coefficient in each group. So the average permeability coefficient of the layer will be

got. The equivalent average permeability coefficient $\overline{K_i}$ is used to replace the permeability coefficient of the layer whose permeability coefficient has changed. Considering one group in radial, the unit width discharge through the cell is q_i:

$$q_i = K_i \times \frac{\Delta H_i \times \Delta L_i}{\Delta S_i} \tag{12}$$

Where $\triangle H_i$ is hydraulic head difference of the no.i cell; $\triangle L_i$ is average length of no. i cell along equipotential line; $\triangle S_i$ is average length of the seepage line. The difference of hydraulic head $\triangle H_i$ of the cell can be calculated:

$$\Delta H_i = \frac{q_i \times \Delta S_i}{K_i \times \Delta L_i} \tag{13}$$

For the discharge along the streamline through each cell is the same, the difference of hydraulic head ΔH equals to the sum of the differences of hydraulic head of each cell:

$$\Delta H = \sum \Delta H_i \tag{14}$$

Supposing the average permeability coefficient along the streamline is $\overline{K_i}$, so the discharge can be expressed approximately as follows:

$$q = \frac{2\pi \overline{K}(H_0 - H)T}{m \cdot \ln(\frac{2a}{r_w})} \tag{15}$$

Where m is the number of cells around the circle.
From Eq(12), (13)，average permeability coefficient $\overline{K_i}$ can be expressed as follows:

$$\overline{K_i} = \frac{\sum \frac{\Delta S_i}{\Delta L_i}}{\sum \frac{\Delta S_i}{K_i \times \Delta L_i}} \tag{16}$$

The average coefficient of the next streamline can be got using the same method, and then the total average permeability coefficient K in the field can be calculated.
Supposing the average permeability coefficient along the no. i streamline is $\overline{K_i}$, and discharge is q_i, so

$$q_i = \overline{K_i} \times \Delta L_i \times \frac{\Delta H_i}{\Delta S_i} \tag{17}$$

The total discharge in the seepage field is Q.

$$Q = \sum q_i = K \times \Delta L \times \frac{\Delta H}{\Delta S} \tag{18}$$

From Eq(15), (16) and $\Delta H_1 = \Delta H_2 = \cdots = \Delta H_i = \Delta H$, the total average permeability coefficient K can be got:

$$K = \frac{\sum \overline{K_i} \times \frac{\Delta L_i}{\Delta S_i}}{\frac{\Delta L}{\Delta S}} \tag{19}$$

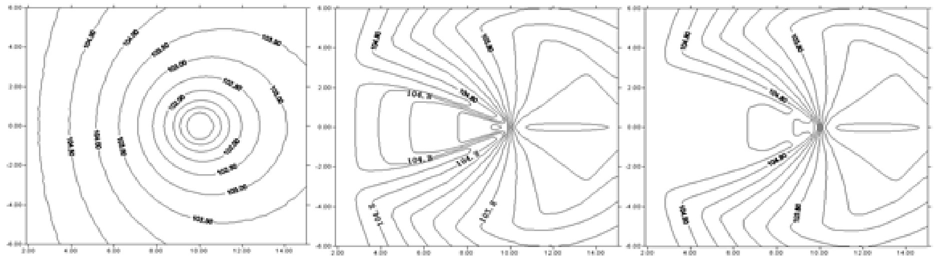
Supposing the hydraulic head of the river is constant, the second hydraulic head can be got by $H_{i,t} = H_{i+1,t} - \Delta H_{i,t+\Delta t}$, where hydraulic head has included kinematic hydraulic head. By this way, hydraulic head and permeability coefficient of each point in the field can be studied, and the total discharge can be calculated. The discharge of each cell q_i can be distributed by the total discharge, $q_i = Q \times \frac{\overline{K_i}}{K}$. So the iterative calculate can be performed, and the new discharge after the period of Δt can be calculated.

3. Case Study

Supposing the layer is consisted of two different diameters, the diameter of the large grain is 25mm, the diameter of small grain of 0.6mm. The permeability coefficient of the large grains is 38cm/s, and the permeability coefficient of the small grains is 0.019cm/s. The water head of the river is 150m. The ground elevation around the piping well is 145m, and the length between the piping well and the river is 10m. The radius of the piping well is 0.5m.

3.1 Hydraulic head near the piping well after piping taking place

The difference of hydraulic head before and after piping in the model can be calculated. Before piping taking place permeability coefficient in the layer is the same, and the distribution of hydraulic head is shown in Figure 3(a). Hydraulic gradient near the river changes more significantly. With the development of piping, more and more small grains is carried away, permeability coefficient of the layer changes. The nearer the point to the piping is, the larger permeability coefficient is. The distribution of hydraulic head is shown in Figure 3(b). From Figure 3(b), hydraulic head near the piping is larger than before, and permeability coefficient near the river is significantly larger. When the discharge is steady after piping taking place, the distribution of hydraulic head is shown in Figure 3(c). Small grains near the river are all carried out, and form the piping passage eventually.

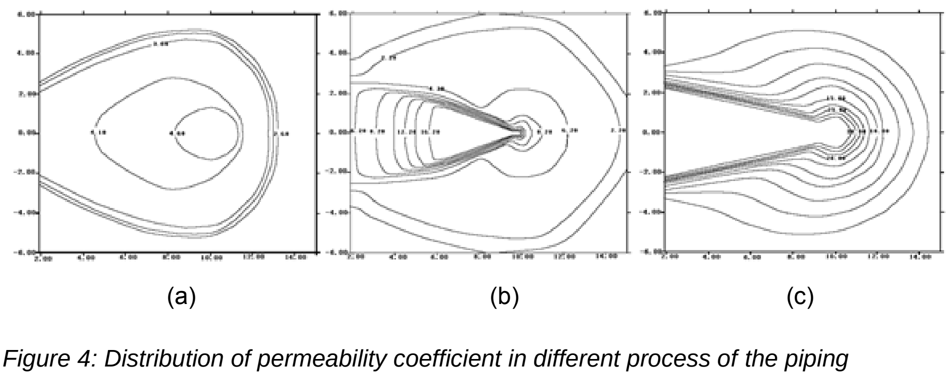


(a) (b) (c)

Figure 3: Distribution of hydraulic head in different process of the piping
(a) initial period of piping (b) during the process of piping (c) the later period of the piping

3.2 Relation among piping, permeability coefficient and flow velocity

By the calculation, we find that there is no rigorous limit among piping and permeability coefficient. For cohesionless soil when the overlying is penetrated, small grains are all able to be carried away and piping well forms. When K_1=36cm/s (D=25mm), K_2=0.019cm/s (d=0.6mm), and a=10m, the permeability coefficient curve can be got, shown in Figure 4(a). The difference of permeability coefficient in the zone is large. The zone of gushing grains is like a circle whose center is piping well. There is a gap beside the river. Permeability coefficient ranges from 2.0-4.0cm/s. From Figure 4 we can find that there is an obvious critical surface. When hydraulic head in the piping well is rising during the development of the piping, hydraulic gradient descend, and the critical surface shrinks, shown in Figure 4(b). The gushing grain mostly come from the dam side. Permeability coefficient in the new critical surface is larger than before, and it descends toward to the dam. The piping passage forms eventually, shown in Figure 4(c).



(a) (b) (c)

Figure 4: Distribution of permeability coefficient in different process of the piping

(a) initial period of piping (b) during the medium process of piping (c) the period after the piping passage forms

4. Conclusion

Piping is a random phenomenon, and it is affected by grain sort, grain composition, difference hydraulic head, etc. Permeability coefficient of the layer is determined mostly by small grains before piping occurring. Once piping happens, and small grains will be carried away, permeability coefficient of the layer will be asymmetry. Permeability coefficient of the layer becomes to be determined by large grains, and dangerous piping passage may eventually form. In this paper, the layer is supposed consisted of two spheres with different diameters. The flow field is be divided into cells under the assumption of the layer is homogenous. When the small grains are carried away, permeability coefficient becomes asymmetry. For the cell is little, permeability coefficient of the cell is constant. By the Darcy law, we can calculate the discharge, hydraulic head, etc. Though the model studies the two ideal sphere, it can be applied to actual stratum. This model has taken specific point in flow field into account, and so it reflects that absolute passage has effection on piping. From the analysis of this model we can conclude that piping is liable to happen in the normal direction to the dam.

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