Research on Pressure of Dike Leakage Hole Inlet Closure

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Abstract. When the leakage inlet of a levee embankment is sealed, a transient flow similar to "water hammer" occurs, and the instantaneous cyclic changes in pressure can cause deformation or damage to the sealing material. At the same time, it can cause the alternating expansion and compression of the soil in the inlet section, which can further intensify erosion and collapsing, and lead to secondary damage to the leakage. This paper regards the sealing of levee embankment leakage as a valve closure operation of a thick-walled pipe inlet section, and based on simulation calculation methods, analyzes the pressure of sealing blockage at floodgate leakage inlet. The simulation results show that the pressure peak value appears at the inlet of the leakage, and the instantaneous pressure at the hole gradually decreases in a periodic trend. When the water depth at the inlet is 2.0m, the instantaneous static pressure of the seal drops from 1.05atm to 0.02atm and lasts for about 0.25s. Within the next 0.61s, the pressure continuously increases to a maximum value of 2.0atm. The first cycle of pressure change is about 1.62s, and the average cycle is about 1.20s. In order to ensure the success rate of sealing leakage, the water hammer pressure generated by the instantaneous sealing should be reduced, and the pressure that the sealing materials and equipment bear should be reduced or dispersed. Based on this, the concept of "step-by-step sealing" inside the hole is proposed, instead of single-level sealing of the hole.

Keywords: Levee embankment, Leakage, Sealing, Water hammer pressure, Step-by-step sealing.

1. Introduction

The rescue of levee embankment leakage should follow the principle of "Inlet Plugging and Outlet Anti-filtration"[1, 2]. It is important for successful rescue to seal the inlet in a timely and rapid manner. According to rescue materials and methods, "inlet plugging" can be divided into three types: plugging, capping, and berm. Among them, plugging refers to the use of soft wedges or special equipment to plug into the inlet, tightly fitting with the hole wall to block or reduce water flow. Capping refers to the use of large area materials or special equipment to cover the leakage inlet, extending the seepage path of the hole, and slow down the flow rate inside the hole. When the aforementioned "inlet plugging" measures are adopted to seal the leakage, the sealing materials will quickly cover or enter the hole under the action of water flow, which is prone to instantaneous pressure changes near the inlet and bears the impact similar to "water hammer"[3]. In case that the allowable pressure of the sealing materials is less than the water hammer pressure, deformation and damage will occur, forming new seepage paths, intensifying local soil erosion at the inlet, expanding the danger situation, and leading to rescue failure.

The pressure level of the sealing materials at the moment of covering or entering the hole during the rescue can be determined, which can provide data support for the selection of sealing materials, the development of sealing equipment, and the improvement of sealing process. Based on the construction of leakage in model embankments, this paper analyzes the water hammer wave velocity inside the hole, and uses two methods (traditional water hammer empirical formula and simulation calculation) to analyze and calculate the sealing pressure at the inlet of the embankment leakage.

2. Differential Equation for Water Hammer in Pressure Pipes

The differential equation for water hammer in pressure pipes can be derived based on Newton's second law and the law of conservation of mass[4], including motion equation and continuity equation, reflecting the changes in velocity and head in elastic water hammer theory. The motion equation is:

$$\frac{\partial H}{\partial x}+\frac{1}{g}\frac{\partial v}{\partial t}+\frac{v}{g}\frac{\partial v}{\partial x}+\frac{f}{D}\frac{v|v|}{2g}=0 \tag{1}$$

The continuity equation is:

$$\frac{\partial H}{\partial t}+v\left(\frac{\partial H}{\partial x}+\sin\theta\right)+\frac{a^2}{g}\frac{\partial v}{\partial x}=0 \tag{2}$$

Wherein: H is the piezometric head; x is the position coordinate; v is the velocity in pipe; t is the time; D is the pipe diameter; f is the frictional resistance coefficient; θ is the angle between the pipe axis and the horizontal line; is the propagation speed of water hammer waves.

The characteristic line method is a commonly used numerical calculation method for water hammer. The partial differential equation should be transformed into an ordinary differential equation, and the pressure and flow rate of the fluid should be calculated to obtain the transient response process, and then the basic differential equation for water hammer can be solved in combination with the initial and boundary conditions.

3. Velocity of Water Hammer Wave inside the Leakage Hole

The embankment leakage hole can be regarded as a circular pressure pipe. In water hammer calculation, the propagation speed a of water hammer waves has a significant impact on the water hammer pressure.

For thin-walled circular pipes, the propagation velocity a of water hammer waves in pressure pipes obtained based on the continuity equation is:

$$a=\sqrt{\frac{\frac{K}{\rho}}{1+\frac{K}{E}\frac{D}{e}c_1}} \tag{3}$$

Wherein: K is the elastic modulus of water; ρ is the density of water; E is the elastic modulus of the pipe wall; D is the pipe diameter; e is the pipe wall thickness, and; c_1 is the pipe expansion coefficient. For thick-walled elastic pipes, c_1 is:

$$c_1=\frac{2e}{D}(1+\mu)+\frac{D(1-\mu^2)}{D+e} \tag{4}$$

Wherein, μ is the Poisson's ratio of the pipe wall material.

When the embankment leakage hole is regarded as a circular pressure pipe that runs through the embankment body or foundation, it should be fixed along the entire line and not allowed to move longitudinally. At the same time, the pipe wall thickness e in the hole is much greater than the hole diameter D, $c_1 \approx \frac{2e}{D}(1+\mu)$, obtaining:

$$a=\sqrt{\frac{\frac{K}{\rho}}{1+\frac{2K}{E}(1+\mu)}} \tag{5}$$

The water hammer wave length t is:

$$t = \frac{2l}{a} \tag{6}$$

Wherein: l1 is the pipe length.

When the closure time is $T_s < \frac{2l}{a}$, a direct water hammer is generated, and the length of direct water hammer pressure can be calculated based on the Joukowsky formula:

$$\Delta p = \rho a v_0 \tag{7}$$

Wherein: ρ is the water density; v_0 is the water velocity inside the pipe.

4. Analysis of Pressure for Leakage Sealing

When the characteristic line method is used for numerical simulation of leakage sealing, the inlet is replaced by a valve model. When the leakage is not sealed, the valve is in a fully open state, and the corresponding valve will be closed immediately after the sealing material or equipment covers the leakage. The sealing of the inlet displays the process of the valve from fully open to closed.

The model embankment for embankment leakage (Figure 1) has a top width of 3.0m, a bottom width of 15.0m, a slope on the water side of 1:2, and a slope on the land side of 1:1. the leakage is 0.5m above the ground and is generally arranged horizontally, with a length of 13.5m and a diameter of 0.1m. The water depth at the inlet can reach 3.0m. The material of the hole (pipe) wall is generalized as "plastic and implastic clay". Considering the saturation of the leakage hole wall soil after the formation of hole, the elastic model is taken as 5Mpa, and the Poisson's ratio 1 is taken as 0.30. EμAccording to Equation (5), the propagation speed of water hammer waves is 43.86m/s.

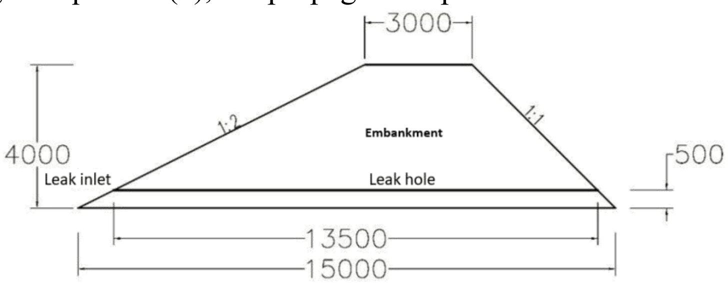


Figure. 1 Cross Section of Model Embankment (unit: mm)

AFT Impulse is used to generalize the aforementioned embankment leakage into the water transport pipe model shown in Figure 2. River is a constant water level reservoir, and Leak inlet is the inlet section of the leakage, with a length of 0.05m; Plugging equipment is a pipe valve, representing a leakage sealing device, with a valve flow coefficient of 200; K_V Leak is a pipe representing leakage, with a length of 13.5m; Outlet is the outlet of the leakage, set to free flow.

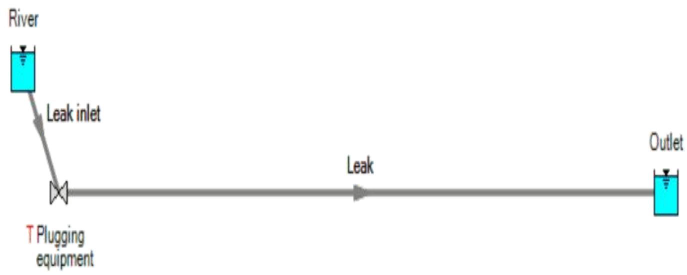


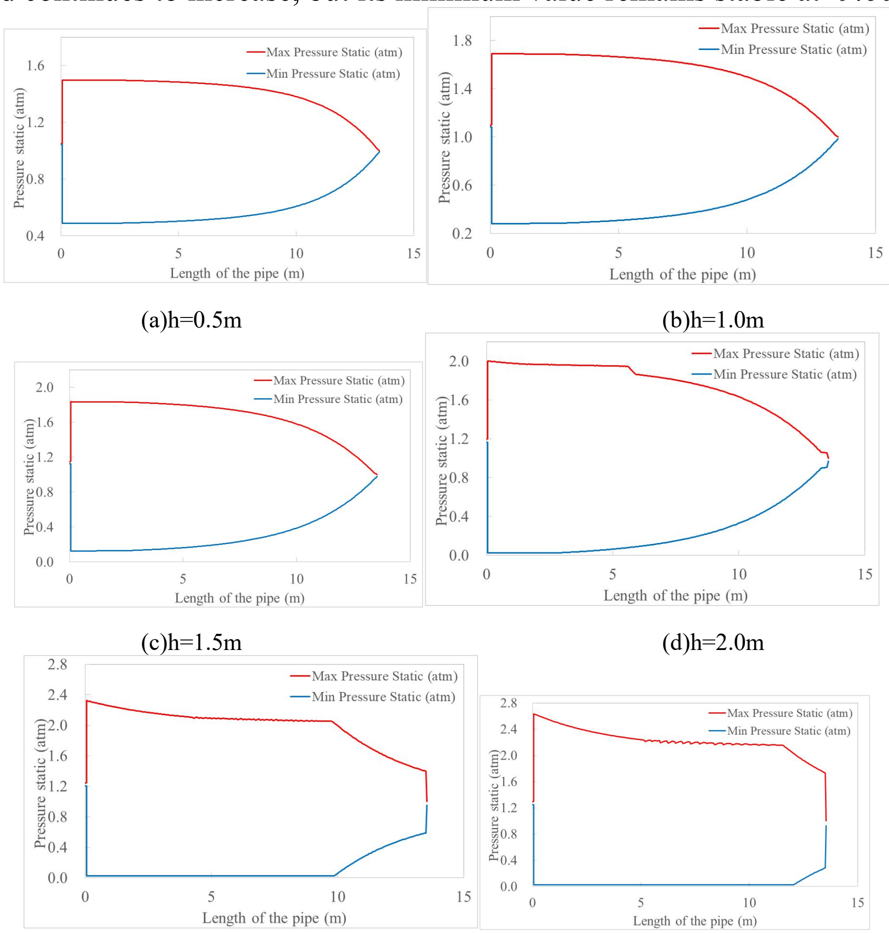
Figure. 2 Model for Calculating Water Hammer in Embankment Leakage Sealing

In the practice of rescue for embankment leakage, when the sealing device covers the inlet of the leakage, the corresponding pipe inlet valve is closed rapidly. The total simulation time for the simulation calculation is 50.0s, where the valve starts to close at 2.0s and the closing process T_s lasts for 0.5s. If it is less than the water hammer wave length t (0.62s) calculated according to Equation (6), a direct water hammer will occur. According to the above valve closing plan, transient analysis and calculation will be conducted separately.

4.1 Extreme value and position of water hammer pressure

The maximum and minimum static pressure along the pipe is shown in Figure 3. When the valve is closed, a direct water hammer occurs in the pipe, and the extreme water hammer pressure value gradually decreases along the direction of the water flow in the pipe. The maximum and minimum pressure values occur at the outlet of the valve (corresponding to the vicinity of the leakage inlet).

The extreme pressure values at the valve outlet under different water depth are shown in Table 1. With the increase of water depth, the maximum water hammer pressure correspondingly increases, reaching 2.63atm at a water depth of 3.0m; the minimum water hammer pressure decreases accordingly. When the water depth is greater than or equal to 2.0m, the minimum static pressure value stabilizes at 0.02atm, and the pipe is close to a vacuum state. According to the hydraulic slope data (Figure 4), when the water depth is greater than or equal to 2.0m, the maximum value at the piezometer head continues to increase, but its minimum value remains stable at -9.60m.



(a)h=0.5m (b)h=1.0m

(c)h=1.5m (d)h=2.0m

(e)h=2.5m (f) h=3.0m

Figure. 3 Distribution of Static Pressure Extreme Values along the Pipe

Table 1. Water Hammer Pressure at Valve Outlet under Different Water depth

Water depth at the inlet (m)	Maximum water hammer pressure (atm)	Minimum water hammer pressure (atm)	Maximum value at the piezometer head (m)	Minimum value at the piezometer head (m)
0.5	1.50	0.49	5.64	-4.80
1.0	1.69	0.28	7.64	-6.94
1.5	1.83	0.12	9.13	-8.56
2.0	2.00	0.02	10.84	-9.60
2.5	2.32	0.02	14.19	-9.60
3.0	2.63	0.02	17.40	-9.60

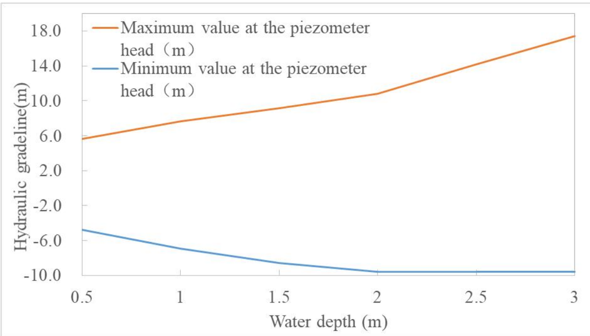


Figure. 4 Changes in Water Depth - Hydraulic Slope

4.2 Changes in water hammer pressure at the valve outlet

When the valve is closed, the water hammer pressure of the pipe shows a periodic change with a gradually decreasing trend. For example, if the water depth at the inlet is 2.0m, the changes in pressure at the valve outlet are shown in Figure 5. The duration of the pipe valve from fully open to fully closed is 0.5s, and the instantaneous static pressure of the closure drops from 1.05atm to 0.02atm and lasts for about 0.25s. Within the next 0.61s, the pressure continuously increases to a maximum value of 2.0atm. Afterwards, the pressure value shows a periodic decrease, and the amplitude tends to stabilize after 30-35, with the maximum pressure stabilizing at 1.2atm. The first cycle of pressure change is about 1.62s, and the average cycle is about 1.20s.

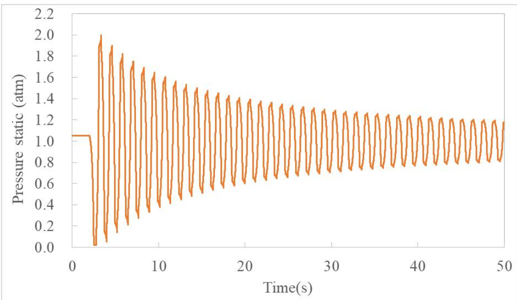


Figure. 5 Changes in Static Pressure at the Outlet When the Valve Is Closed (h=2.0m)

4.3 Changes in water hammer pressure at the inlet of the leakage

As mentioned earlier, when "inlet plugging" measures are used for the embankment leakage, the sealing process is similar to the pipe "valve closing" process, and can be considered as only "single-level sealing" of the inlet. Under the single-level sealing, a high water hammer pressure will be generated at the inlet of the leakage. When the water depth is 1.0m, the maximum water hammer pressure can reach 1.69atm. When the water depth is 2.0m, the maximum water hammer pressure can reach 2.00atm. When the water depth is 3.0m, the maximum water hammer pressure can reach 2.63atm.

The periodic variation ("drop - rise - drop") of water hammer pressure in a short period continues to act on the sealing material and the inlet section of the leakage. Higher pressure can cause deformation and even failure of the sealing material, and periodic pressure can also trigger a rapid alternating change in the "expansion - compression - expansion" of the soil in the inlet section of the leakage, exacerbating soil deformation, collapse, and erosion, resulting in secondary damage to the leakage. Moreover, new seepage channels may be formed between the sealing material and the soil at the leakage due to material deformation and soil erosion, which may worsen the danger situation or cause rescue failure.

5. Measures to reduce the instantaneous water hammer pressure during sealing

In order to ensure the success rate of sealing leakage of a levee embankment, the water hammer pressure generated by the instantaneous sealing should be reduced, and the pressure that the sealing materials bear should be reduced or dispersed. The leakage sealing equipment at the inlet is mainly affected by the flow rate, and the time from approaching the hole to fully covering the hole cannot be accurately controlled, making it difficult to change direct water hammer into indirect water hammer, or reduce water hammer pressure by increasing the "valve closing time". To solve the above problems, the sealing equipment can be improved and optimized, and step-by-step sealing equipment can be developed for embankment leakage[5-7] (Figure 6), and "single-level" sealing at the inlet can be transformed to "step-by-step" sealing at the inlet and inside the hole.

The step-by-step sealing equipment for embankment leakage consists of seven parts: the position indicator for the leakage inlet, floating objects in the duckweed shape, conical ropes, high water absorbent resin balls, tandem ropes, counterweights, and traction ropes. During sealing and rescue, the floating objects in the duckweed shape are fixed on the slope of the embankment leakage inlet, playing a fixed support role. Due to the use of a hollow circular structure, when the equipment covers the inlet, there are no water hammer effects. After the high water absorbent resin ball enters the hole, it quickly absorbs water and expands and tightly combines with the hole wall, forming a tandem enclosed spaces inside the hole, achieving the effect of gradual sealing and leakage stopping inside the hole.

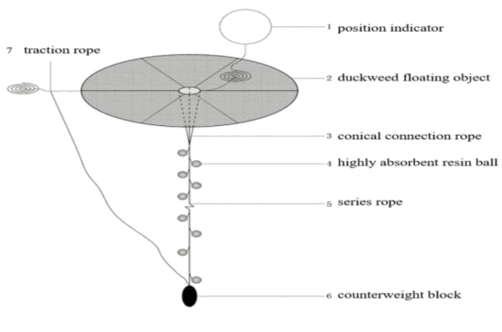


Figure. 6 A duckweed dam leak plugging device

6. Conclusion

The leakage sealing is similar to the "valve closing" in pipe systems. The simulation calculation results show that the embankment leakage bears a significant periodic change in water hammer pressure during sealing, far exceeding the static water pressure at the leakage inlet. When the material on the hole wall is relatively dense, due to the similar water hammer pressure and water vaporization pressure, there will be a flow interruption at the moment of sealing, forming a cavity, at this time, the pressure will rapidly increase, causing serious damage to the soil on the hole wall.

The step-by-step sealing equipment for embankment leakage can reduce the water hammer pressure generated at the inlet and inside the hole, and disperse it step by step to avoid secondary damage to the leakage inlet and hole.

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