

PRESSURE FORCE AT PIPE ENTRANCE DURING CLOSURE PROCESS

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Safety of detention basins is an increasing concern in urban areas. During a storm event, the subsurface currents in a basin create unseen hazards. As soon as the outfall pipe entrance becomes plugged, the pressure force quickly switches from flow-momentum force to water-weight static force. The vortex flow near the outfall structure presents a pressure force that can cause loss of life. According to the Newton's third law, the pressure force acting on the pipe entrance can also be interpreted as the suction force in the flow direction or into the pipe tube. This paper presents a simple model to quantify the pressure force when the pipe entrance is gradually clogged. Examples illustrated in this paper reveal that the pressure force generated by plugging a pipe can be lethal.



*Photo 1 Subsurface Currents
Upstream of Submerged Culvert*



*Photo 2 Turbulent Jets and Cross Waves
Downstream of Submerged Culvert*

FLOW AND FORCE DURING CLOSURE

Assuming that the clogging begins from the bottom of the pipe opening, the hydraulic parameters associated with the flow can be related to the central angle in Figure 1. For a specified angle, the opening depth, Y , and area, A , can be calculated as:

$$Y = D - \frac{D}{2}(1 - \cos \theta) \quad (1)$$

$$A = A_F \left[1 - \frac{1}{\pi} (\theta - \sin \theta \cos \theta) \right] \quad (2)$$

$$A_F = \frac{\pi D^2}{4} \quad (3)$$

In which D = pipe diameter, θ = clogging angle defined in Figure 1, and A_F = pipe sectional area.

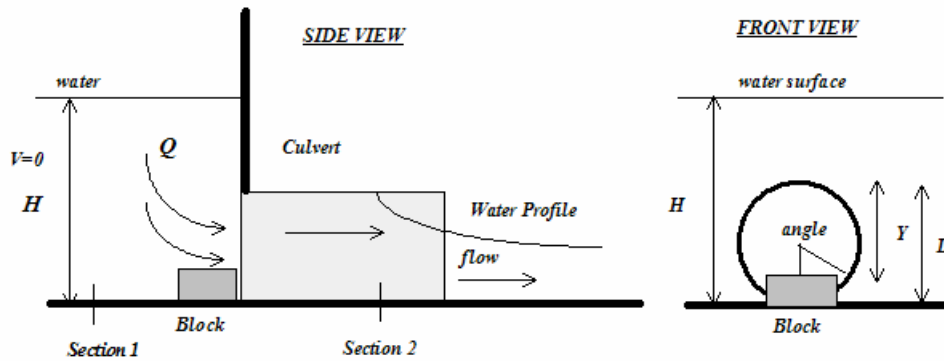


Figure 1 Flow through Clogged Pipe

Applying the orifice formula to this case, the flow rate entering the opening area is estimated by:

$$Q = C_o A \sqrt{2g \left(H - \frac{Y}{2} \right)} \quad (4)$$

in which Q = flow rate, C_o = orifice coefficient including the loss between Sections 1 and 2, g = gravitational acceleration, and H = water depth in pool. The flow-full velocity through the pipe is:

$$V_F = \frac{Q}{A_F} \quad (5)$$

In which V_F = flowing full velocity. Define the control volume of flow to be between Sections 1 and 2. The release at Section 2 is exposed to air. In general, the outfall culvert is so short that the friction force along the pipe walls can be ignored. As a result, the pressure force between Sections 1 and 2 is calculated as:

$$F = \gamma \left(H - \frac{D}{2} \right) A_F - \rho Q V_F \quad (6)$$

in which F = pressure force between Sections 1 and 2, γ = water specific weight and ρ = water density. The clogging condition can be expressed by the clogging angle defined in Figure 1. For instance, when $\theta = 0$, the pipe is not clogged at all, and when $\theta = \pi$, the pipe is completely

plugged. Eq 6 for the former represents the flow momentum force, and the latter converts Eq 6 to hydrostatic force as:

$$F = \gamma(H - \frac{D}{2})A_F \text{ when } V_F = 0 \quad (7)$$

DESING EXAMPLE

This simple model is applied to a 24-inch pipe under 9 feet of water. The closure process is divided into seven stages, starting with a 100% unclogged condition. The predicted flow rates and hydrostatic forces are summarized in Table 1 and plotted in Figure 2 as well.

| Clogging Angle <i>radians</i> | Opening Area <i>A</i> <i>ft²</i> | Opening Depth <i>Y</i> <i>ft</i> | Orifice Flow rate <i>Q</i> <i>cfs</i> | X-section Velocity <i>V_F</i> <i>fps</i> | 1.0% of Pressure Force <i>lb</i> |
|----------------------------------|---|--|---|--|-------------------------------------|
| | Eq 2 | Eq 1 | Eq 4 | Eq 5 | Eq 6 |
| 0.000 | 3.14 | 2.00 | 46.35 | 14.75 | 9.06 |
| 0.524 | 3.05 | 1.87 | 44.82 | 14.27 | 9.49 |
| 1.047 | 2.53 | 1.50 | 36.70 | 11.68 | 11.53 |
| 1.571 | 1.57 | 1.00 | 22.44 | 7.14 | 14.13 |
| 2.094 | 0.61 | 0.50 | 8.63 | 2.75 | 15.45 |
| 2.618 | 0.09 | 0.13 | 1.26 | 0.40 | 15.68 |
| 3.142 | 0.00 | 0.00 | 0.00 | 0.00 | 15.68 |

Table 1 Predicted Closure Pressure Forces on 24-inch Pipe Entrance under 9-ft Water

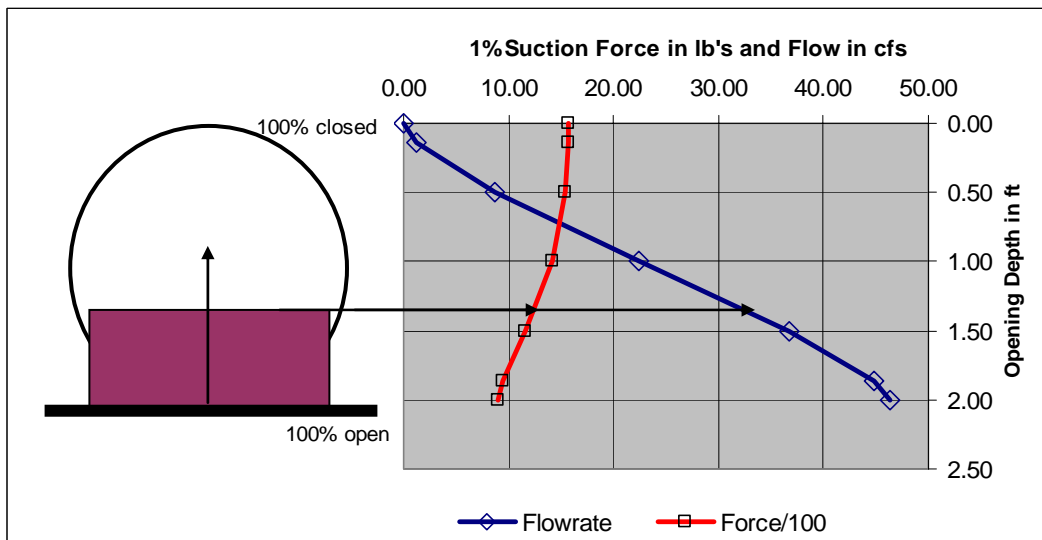


Figure 2 Pressure Force on 24-inch Clogged Pipe Entrance under 9-ft Water

For this case, the discharge decreases from 46.4 cfs when the pipe is completely open to no flow when the pipe is 100% clogged. Correspondently, the pressure force increases from 255 to 1568 pounds. At closure, the hydrostatic force is 1568 pounds for this case. Eq 6 provides a transition from flow dynamic to static condition.

DESIGN SCHEMATICS

Eq 5 can be further normalized using the flow inertial force. As a result, Eq 5 becomes

$$\frac{P}{\rho V_F^2} = \frac{g(H - \frac{D}{2})}{V_F^2} - 1 \quad (8)$$

$$P = \frac{F}{A_F} \quad (9)$$

In which P = pressure in flow. Eq 8 is the relationship between Euler number and Froude number. Euler number represents the ratio of flow pressure force to inertial force and Froude number is the ratio of flow inertial force to water body weight. Based on the basic definition, Eq 7 is re-written as:

$$E_u = \frac{1}{F_r^2} - 1 \quad (10)$$

In which E_u = Euler number and F_r = Froude number. These two dimensionless variables are defined as:

$$E_u = \frac{P}{\rho V_F^2} \quad (11)$$

$$F_r = \frac{V_F}{\sqrt{gH^*}} \quad (12)$$

$$H^* = H - \frac{D}{2} \quad (13)$$

During the closure process, Eq 10 describes the change of the force in the flow from the pressure force represented by Euler number to the gravity force represented by Froude Number. Mathematically, Eq 10 has a singular point at $V_F=0$ or $F_r=0$ when the pipe entrance is completely plugged. When $F_r=1$ or $E_u=0$, the depth in the pool becomes too shallow to produce a pressurized flow through the outfall pipe. As a result, it is a case of open channel flow.

CLOSING

The example used in this paper implies that when a child or small animal was dragged by the water currents into the outfall pipe entrance, the water flow would quickly slow down and the hydrostatic force of several hundred pounds would be immediately developed to continuously hammer the body into the pipe.

From the aspects of aesthetics and maintenance, safety criterion recommended for retention and detention pond designs emphasize the allowable water depth, stable bank slopes, fence, and guard rails. Trash rack is often considered for debris control only. In fact, a trash rack is the most economic measure to protect the outfall pipe from debris clogging and also to sustain a continuous flow through the outfall pipe. Obviously, an inclined trash rack provides assistance for a child or animal to climb up. A vertical trash rack prevents a child from plugging the pipe entrance. Once the outfall pipe is getting plugged, the acting force quickly switches from the dynamic to hydrostatic force. Case study indicates that the hydrostatic force of 4-foot water on a 24-inch clogged pipe can be lethal.

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