

Guo, James C.Y and Jones, J (2008). "Pinning Force During Closure Process at Clocked Pipe Entrance", ASCE J. of Irrigation and Draining Engineering, Nov, 2nd-review

PINNING FORCE AT BLOCKED PIPE ENTRANCE

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Abstract:

The high design standards for the preservation of urban water environment result in more detention basins in the residential areas. The steep channel and outfall pipe from a detention basin can be hazardous to children and small animals. During an event, a trapped person may flow with water towards the outfall entrance. When the outfall pipe is gradually blocked, the flow force acting on the blocking body can be pinning at the beginning to eventually deadly. It is not clear as to how to quantify the pinning force on the block during the closure of flow because the number of unknown forces is greater than the number of equations for force balance. This paper presents a new approach using the method of superposition to calculate the pinning force with and without a blockage at the culvert entrance. The analysis conducted in this paper verifies that the pinning force on the clogging block is dominated by the flow dynamic force until the flow becomes discontinued. As soon as the hydrostatic force is developed, the pinning force can be lethal. This study confirms that an outfall pipe shall be protected by a trash rack with its surface area 4 times the culvert opening area. As long as the continuity of flow is sustained by the blocked rack, the hydrostatic force will not be developed or a chance for survival remains.

Keywords: Dynamic Force, Hydrostatic, Trash Rack, Outfall Culvert, Safety

INTRODUCTION

Over the last decade, the Federal Clean Water Act has suggested to add more retention and detention basins to residential areas for the purpose of preservation of the water environment (Mays 2001). Often storm water basins are blended into the landscaping in parks, sport fields, and picnic areas. With a mild bank slope, a landscaped, dry stormwater detention area can be an attractive feature for children and small animals. The steep channels and outfall culvert in the basin are hazardous during a storm event because of the high water velocities (Allred-Coonrod 1994). During a storm event in July 2001, an 8-years-old boy and his dog enjoyed plunging into the 5-ft pool that has a 36-inch (91.4-cm) culvert (Rocky Mountain News July 30, 2001). The subsurface water currents created unseen hazards in the loaded basin. This boy was sucked into the culvert entrance and then flushed through a dark tunnel of 40 feet. As recommended, the culvert entrance is protected by a rack that can intercept floating debris in water and also prevent a person from being washed into the culvert. Considering that the pinning force from the water flow on a human body landed on the rack can also be deadly, the laboratory study was conducted to conclude that a parabolic rack can perform better than the flat because the uplift force supported from the rack's curved surface can assist the human body to float up (Weisman 1989).

This paper presents an investigation on how the pinning force is developed from a gradually plugged pipe entrance, using a new method of superposition to calculate the forces acting on the pipe entrance walls and the blocking object as well. The case study using this algorithm reveals that the pinning force gradually increases due to the decrease in the flow dynamic force. As soon as the pipe entrance is getting plugged, the pinning force increases exponentially to its maximum in order to balance the hydrostatic force. For a typical 2-m deep detention basin, the hydrostatic force at an outfall pipe entrance can be more than 10 times the flow dynamic force. Based on the force comparison, it is recommended that the outfall pipe be protected by a rack with such a large surface area that can sustain the continuity of flow under the critical clogging condition.

FLOW AND FORCE

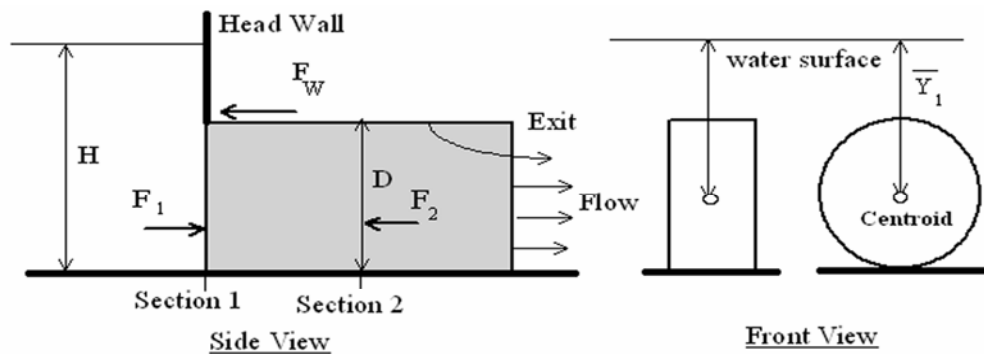
According to the momentum principle, the flow force consists of dynamic and hydrostatic components. All forces on a defined control volume must be balanced with the change of flow momentum (Guo and Maxwell 1984). The outfall pipe from a basin is usually tied into the downstream channel. Define the control volume of water flow to be between Sections 1 and 2 in Figure 1. Section 1 is located at the culvert entrance and Section 2 represents the outfall condition that is subject to the specified tailwater depth. In general, the outfall culvert is so short that the friction force along the pipe walls can be ignored. As a result, the balance of forces between Sections 1 and 2 is formulated as (Guo 2006):

$$F_1 = F_2 + F_W + F_B \quad (1)$$

$$F_1 = \gamma \bar{Y}_1 A_1 + \rho Q V_1 \quad (2)$$

$$F_2 = \gamma \bar{Y}_2 A_2 + \rho Q V_2 \quad (3)$$

in which F = force associated with flow, F_W = external force from walls on flow, F_B = external force from the clogging block to flow, γ = water specific weight, \bar{Y} = depth to centroid of flow area, A =flow area, Q = flow in pipe, and ρ = water density. The subscripts, 1 and 2, represent the variables of Sections 1 and 2. All forces in Eq 1 are a vector component in the direction of the flow. In practice, it is a dilemma to apply three equations, Eq's 1, 2, and 3 to solve for four unknown forces, including F_1 , F_2 , F_B , and F_W . In this paper, a new method of superposition was derived to provide the solution progressively, starting with the clear entrance as the base condition to firstly solve for the force from walls, F_W . Next, the additional blockage is introduced to Eq 1 to solve for the force, F_B , acting on the block. This two-step approach provides a practical tool to conduct forensic studies for analyzing forces in a drowning case.



(Figure 1 Flow through Outfall Culvert)

Base Condition

As aforementioned, the base condition is defined with a clear culvert entrance. An outfall culvert from a detention basin is often operated under a high headwater or a full flow through the conduit. Between Sections 1 and 2 in Figure 1, the full flow velocity is calculated as:

$$V_F = \frac{Q}{A_F} \quad (4)$$

$$A_F = \frac{\pi D^2}{4} \quad (5)$$

In which V_F = full flow velocity and D = pipe diameter. Therefore, the flow variables for Sections 1 and 2 are:

$$A_1 = A_2 = A_F \quad (6)$$

$$V_1 = V_2 = V_F \quad (7)$$

$$\bar{Y}_1 = H - \frac{D}{2} \quad (8)$$

$$\bar{Y}_2 = \frac{D}{2} \quad (9)$$

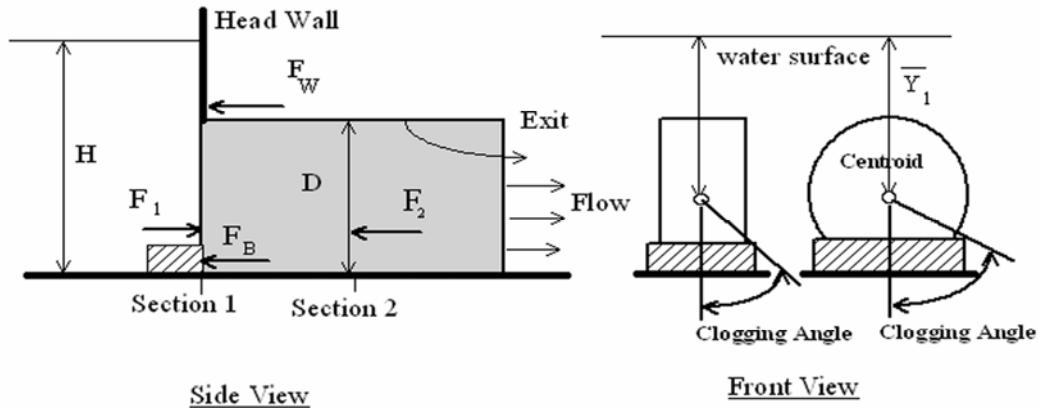
Where H= headwater depth in front of culvert entrance. Aided by Eq's 4 through 9, Eq 1 is reduced to represent the force from the pipe wall on the flow as:

$$F_W = \gamma(H - D)A_F \quad (10)$$

Because there is no blockage at the entrance, $F_B = 0$. Eq 10, in fact, represents the force due to the surcharge depth at the entrance. When H=D, Eq 10 vanishes because the forces in the system are in equilibrium.

Partially Clogged Condition

Sizable debris tends to accumulate in front of the culvert because of the high friction near the bed. Using the circular pipe as an example, all the flow parameters can be expressed by the clogging angle defined in Figure 2.



(Figure 2 Blocked Outfall Culvert)

For instance, when $\theta = 0$, the circular entrance is not clogged at all, and when $\theta = \pi$, the pipe entrance is completely plugged. As illustrated in Figure 2, the flow parameters at the clogged entrance can be related to the central angle as:

$$Y = D - \frac{D}{2}(1 - \cos \theta) \quad (11)$$

$$A = A_F \left[1 - \frac{1}{\pi}(\theta - \sin \theta \cos \theta) \right] \quad (12)$$

In which Y = flow depth, θ = clogging angle, A = flow area, and A_F = pipe sectional area. Applying the orifice formula to this case, the flow rate entering the opening area is estimated as:

$$Q = C_o A \sqrt{2g(H - \bar{Y})} \quad (13)$$

$$V = \frac{Q}{A} \quad (14)$$

in which Q = flow rate, C_o = orifice coefficient including the energy loss between Sections 1 and 2, \bar{Y} = distance to centroid of clogged flow area, V = flow velocity at entrance, and g = gravity acceleration. When the entrance is partially clogged, the pipe still carries a full flow under a high headwater in the basin. Comparing with the base condition, the difference is the flow velocity at the pipe entrance. Repeating the same process, the external force in Eq 1 is derived as:

$$F_W + F_B = \gamma(H - D)A_F + \rho Q(V - V_F) \quad (15)$$

Aided by Eq 10, the force on the clogging block is:

$$F_B = \rho Q(V - V_F) \quad (16)$$

Eq 16 indicates that the force on the clogging block is proportional to the change of flow momentum. Of course, the same conclusion can be derived for box conduits.

Completely Clogged Condition

Assuming that the pipe exit can be freely drained, a completely clogged condition results in a hollow pipe between Sections 1 and 2. With no flow through the entrance, the dynamic forces are vanished. Eq 15 is reduced to:

$$F_B + F_W = \gamma(H - D)A_F \quad (17)$$

Under a closure condition, the blockage acts as the circular gate to sustain the hydrostatic force that is calculated as:

$$F_B = \gamma(H - \frac{D}{2})A_F \quad (18)$$

Aided by Eq 18, the reaction force from the pipe wall is:

$$F_B = F_W \quad (19)$$

In comparison, the hydrostatic force in Eq 18 is much higher than the dynamic force in Eq 16.

APPLCIATION TO FORENSIC STUDY

In a forensic study, it is a common question as to how to quantify the flow force acting on the blocking object, such a human body. For instance, a 750mm circular culvert drains a basin under a headwater depth of 3 meters. The entrance closure process is simulated with seven stages of blockage from $\theta=0$ to $\theta= 1.57$ that is equivalent to the blockage of the low half entrance. As shown in Table 1, when $\theta=0$ or the base condition with a clear entrance, $F_W= 9.74$ kN. For the cases with $\theta>0$, the clogging block reduces the opening area at the pipe entrance. The predicted flow rates and the reaction forces, F_W and F_B , are

calculated and summarized in Table 1. Before the entrance is completely plugged, the force on the block is calculated using Eq 16. As soon as the pipe entrance is plugged, F_B increases to 11.36 kN that is 5 to 10 times the flow dynamic forces. This hydrostatic force continues pushing the block into the pipe.

Clogging Angle radians	At Entrance				Force	
	Flow Depth Y m	Opening Area A m ²	Flow Rate Q cms	Flow Velocity V mps	$F_B + F_W$ kN	F_B kN
	Eq 11	Eq 12	Eq 13	Eq 14	Eq 15	Eq 16
Base Case: 0.00	0.75	0.44	1.90	4.30	9.74	0.00
0.39	0.72	0.44	1.87	4.29	9.84	0.10
0.79	0.64	0.40	1.71	4.26	10.49	0.67
1.18	0.52	0.33	1.37	4.21	11.85	1.52
1.57	0.38	0.22	0.92	4.15	13.68	1.90
Plugged Case: 3.14	0.00	0.00	0.00	0.00	11.36*	11.36*

Note: * calculated by Eq 17 or hydrostatic force

(Table 1 Closure Forces on 750mm Circular Entrance under 3-meter Headwater)

In comparison, the dynamic force is much less than the hydrostatic force. For example, the study case indicates the hydrostatic force is certainly lethal and hardly resisted by a human body. As long as the culvert entrance remains open, the flow dynamic force or Eq 16 acts on the block. In practice, the surface area of a trash rack is recommended to be four times the pipe opening area (USWCM 2001). This study indicates that a large trash rack can avoid a complete blockage. Any person landed on the trash rack can only block a portion of the flow area; as a result, the pinning force on the human body remains to be a fraction of the flow dynamic force. It implies that there is a chance to survive from drowning. A trash rack, at least, can prevent a body from being washed into the conduit.

CONCLUSION

The complexity of force analysis at the pipe entrance is stemmed from not enough equations for the number of unknown forces. This paper presents a new method of superposition to analyze the forces by a two-step procedure, starting with the force on the pipe wall first, and then the force on the clogging block. This approach is applicable to calculate the force acting on a human body or small animal washed into an outfall pipe. In this study, it is concluded that the block at the pipe entrance is subject to the flow dynamic force when the pipe entrance is partially clogged. The flow force can turn into the hydrostatic force when the culvert entrance is completely plugged. The hydrostatic force is proportional to the weight of water. In comparison, the dynamic force is much less deadly than the hydrostatic force. As soon as the hydrostatic force is developed, the human or animal body will be continuously forced into the pipe.

This paper intends to analyze the forces under a gradual closure at a pipe entrance. The unsteady flow is modeled by the orifice flow. This approach may not present a reasonable approximation when the clogging angle exceeds $\pi/2$ or a half of the pipe opening area.

From the aspects of aesthetics and maintenance, safety criterion recommended for detention pond design emphasize the allowable water depth, stable bank slopes, fence, and guard rails (Jones et al. 2006). A trash rack is considered for debris control only (FHWA 1971). In the previous studies (Allred-Coonrod 1994 and Weisman 1989), it was suspected that the pinning force developed on a blocked trash rack can be lethal. In this study, it is concluded that a large trash rack is, in fact, the least-cost measure to protect the outfall pipe from debris clogging and to sustain a continuous flow through the outfall pipe. As

long as the continuity of flow is sustained, the pinning force is only a fraction of the flow dynamic force. Also, an inclined trash rack provides assistance for a child or animal to climb up.

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APPENDIX II

A=flow area,

A_F = pipe sectional area

C_o = orifice coefficient including the energy loss between Sections 1 and 2

D = pipe diameter

F= force associated with flow,

F_w = external force from the entrance walls on flow,

F_B = external force from the clogging block to flow,

g = gravity acceleration

H = headwater depth in front of culvert

Q = flow rate,

\bar{Y} = depth to centroid of flow area,

Y = flow depth

V= flow velocity at entrance

V_F = full flow velocity

γ = water specific weight

θ = clogging angle,

ρ = water density.

Subscripts 1 and 2 represent variables in Sections 1 and 2.