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SUCTION FORCE ON BLOCKED TRASH RACK

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Abstract:
As recommended, culvert entrance in an urban area should be protected with a rack or a grate because urban flood flows are quick, concentrated, and fast. Safety around a storm water facility is an increasing concern for the public. Many forensic cases indicate that a trash rack at the entrance can prevent a human body from being washed into the culvert pipe, and on the other hand, a trash rack increases the flow velocity and results in a pinning force on the human body landed on the rack. It is an on-going debate if the rack is a safe measure for culvert operations. The conventional approach can only provide the total external force acting on a culvert-rack system, including the reaction forces from the wing walls and the rack with or without blockage. This study presents a new method of superposition that can solve the external forces one by one progressively. Results from the case study indicate that the hydrostatic force due to the high headwater in front of the culvert entrance is mainly balanced by the reaction force from the wing walls. The pinning force on the submerged trash rack is mainly the response to the change in the flow momentum force. In comparison, the pinning force is much smaller than the total external force. A pinning force is a normal force on the rack surface. The effort to escape from being pinned on the trash rack is to overcome the friction along the rack surface.

Keywords: Momentum Force, Hydrostatic Force, Trash Rack, Blocked Entrance, Culvert, and Safety.

INTRODUCTION

A culvert is a conveyance conduit for storm water drainage beneath a roadway or other embankments. Culverts functioning under either inlet or outlet control requires a headwater depth at the entrance pool. The water flow through a culvert is a process starting with deceleration through the headwater pool and then acceleration through the contracted entrance. A trash rack is recommended to protect the culvert entrance from sediment and debris for the purpose of long-term maintenance (FHWA 1971). It has been a debate if the trash rack is a safe or hazardous measure to the public. From the field experience, a trash rack can prevent a trapped person to be washed into the culvert conduit (Jones et al. 2006). On the other hand, a trash rack also increases the pinning force to the person landed on the rack surface (Allred-Coonrod 1994, USWDCM 2001). The design of a safety trash rack for a culvert inlet was investigated using a physical model. A parabolic shape of trash rack is recommended to install in front of a culvert entrance because a curved rack surface area provides a push-up force on the block landed (Weisman 1989). All these assertions were based on limited field and laboratory observations. Therefore, it is necessary to develop a method by which the change of flow momentum with respect to the blocking condition can be quantified.

The force analysis on a blocked trash rack is complicated because of the flare-end-section (FES) geometry at the culvert entrance. The major external forces acting on the water flow include the reaction force from the wing walls, the contraction force through the trash rack, and the pinning force on the blocking object (Guo 2006). It is a challenge to solve for three unknown forces simultaneously using the principle of flow momentum. This paper presents a new approach using the method of superposition to calculate the forces acting on the blocked rack. Using this algorithm, the case study reveals that the pinning force on the trash rack is dominated by the flow momentum force. Without a trash rack, the culvert entrance may become plugged. As soon as the flow is discontinued, the lethal hydrostatic force will be developed.

FLOW AND FORCE

A pre-fabricated culvert is often attached with its FES. Illustrated in Figure 1, the trash rack is often laid on top of the FES with an inclined angle between 30 and 40 degrees (USWDCM 2001). The trash rack can effectively intercept debris that blocks a portion of the rack surface. The momentum principle is a vector approach. To apply the momentum principle to the flare-end section, it is reasonable to assume that the vertical force components are balanced by the ground support, and the horizontal forces are balanced in the flow direction.

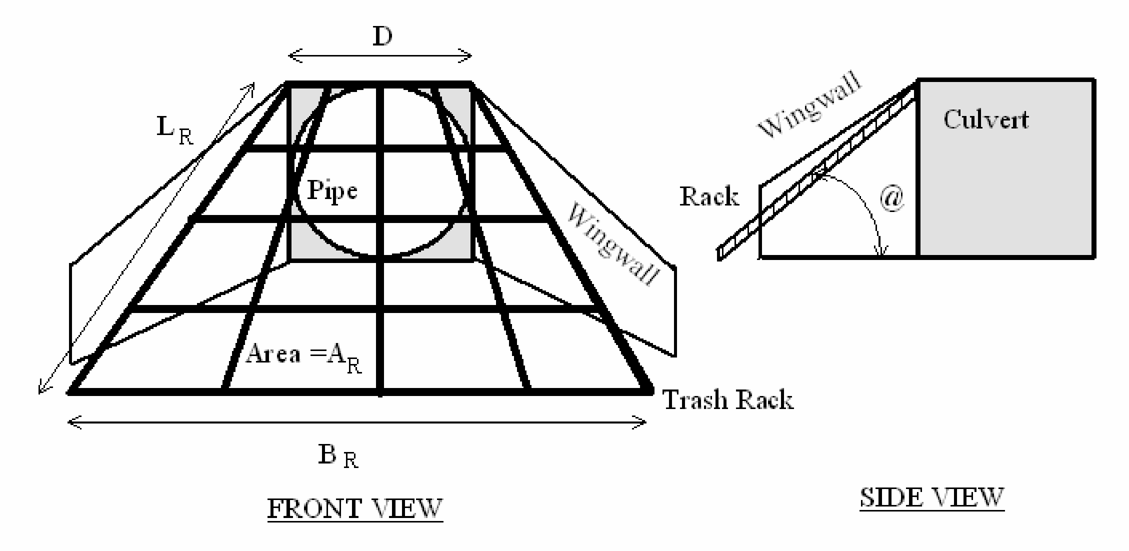

Figure 1 Flare End Section for Culvert Unit

Define the control volume of water flow to be between Sections 1 and 2 in Figure 2. Section 1 is the flare-end section and Section 2 represents the culvert entrance section. In practice, the energy and hydraulic grade lines (EGL and HGL) for a given flow system can be analyzed using the principles of continuity and energy (Mays 2001). As illustrated in Figure 2, the headwater depth in front of the culvert entrance backs up the water surface profile. The balance of forces in the flow direction is formulated as:

$F_1 Sin@ = F_2 + F_W + F_R Sin@ + F_B Sin@$ in the flow direction (1)

$F_1 = \gamma \overline{Y_1} A_1 + \rho Q V_1$ in the direction perpendicular to the rack surface (2)

$F_2 = \gamma \overline{Y_2} A_2 + \rho Q V_2$ in the flow direction (3)

in which F = force acting on water, F_W = reaction force from wing walls, F_R= contraction force through rack, F_B = pinning force on block, γ= water specific weight, $\overline{Y}$ = depth to centroid of flow area, V = cross sectional average velocity, A=flow area, Q= flow in pipe, ρ = water density, and @= inclined angle of rack. The subscripts, 1 and 2, represent the variables of Sections 1 and 2.

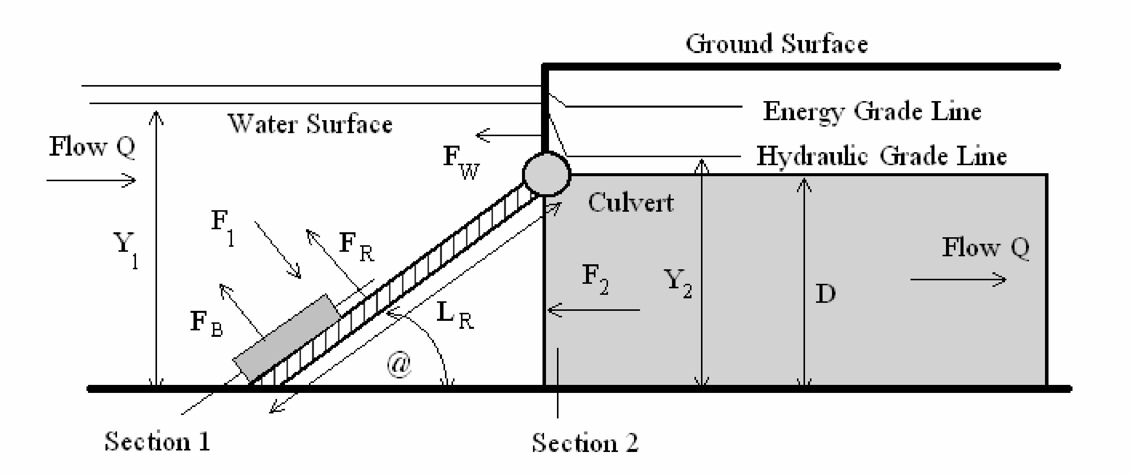

Figure 2 Flow through Trash Rack at Culvert Entrance

Eq 1 has three unknown forces, F_R, F_W, and F_B. It is suggested that Eq 1 be solved using the method of superposition, starting with (1) solving the unknown force, F_W, when the system has no rack, (2) solving the unknown force, $(F_R\,Sin@ + F_W)$ when the rack is added to the system, and (3) solving the unknown force, $(F_R\,Sin@ + F_B\,Sin@ + F_W)$ when the rack is partially blocked. The force difference between the consecutive steps provides an estimate of the new force introduced to the system.

Base Condition

In this study, the base condition is defined with an unprotected culvert entrance. A culvert is often operated under a high headwater for the design flow. Between Sections 1 and 2 in Figure 2, the flow velocities and areas are calculated as:

$$A_1 = A_R \tag{4}$$

$$V_1 = \frac{Q}{A_R} \tag{5}$$

$$A_2 = \frac{\pi D^2}{4} \tag{6}$$

$$V_2 = \frac{4Q}{\pi D^2} \tag{7}$$

$$\overline{Y_1} = Y_1 - \frac{L_R}{2} Sin@ \tag{8}$$

$$\overline{Y_2} = Y_2 - \frac{D}{2} \tag{9}$$

Where A_R = rack's surface area on FES, D= culvert diameter or height, Y = HGL relative to the culvert invert, and L_R = length of rack on FES. Let $F_B = F_R = 0$ in Eq 1. Substituting Eq's (4) through (9) into Eq 1 yields the reaction force, F_W, from the wing walls.

Clear Rack Condition

A rack is formed with steel bars. The area opening ratio is used to calculate the net opening area for water to flow through the rack. The flow velocity at Section 1 is then calculated as:

$$V_1 = V_R = \frac{Q}{nA_R} \tag{10}$$

Where V_R = flow velocity through clear rack, and n = area opening ratio of rack surface, depending on the number and size of steel bars used to form the rack. The rest of variables remain the same as the base condition. Since the rack is not blocked, therefore $F_B = 0$. Aided by Eq 10, Eq 1 can be solved for the sum of $(F_R\ Sin@ + F_W)$. The pinning force on the rack is the difference between $(F_R\ Sin@ + F_W)$ and F_W, or it can be derived as:

$$F_R = \rho \frac{Q^2}{nA_R}(1-n) = \rho V_R Q(1-n) \tag{11}$$

Eq 11 provides the direction solution to the force on the rack. It implies that the presence of a rack does not change the hydrostatic force because the rack is submerged. The pinning force on the rack is solely proportional to the change of the flow momentum or linearly varied with respect to the area opening ratio on the rack surface.

Blocked Rack Condition

A rack intercepts debris in the water flow. For simplicity, the blockage on the rack is represented by the plugged surface area that can be approximated by the projected area on the rack. Define the blocked area to rack surface area ratio, m, as:

$$m = \frac{A_B}{A_R} \tag{12}$$

In which A_B = blocked area on rack surface and m = blocked area ratio to rack surface area. As a result, the flow velocity through the blocked rack is calculated as:

$$V_1 = V_B = \frac{Q}{A_R(n-m)} \tag{13}$$

Where V_B = flow velocity through blocked rack. Aided by Eq 1, 12, and Eq 13, the pinning force on the block landed on the rack surface is derived as:

$$F_B = \rho \frac{Q^2}{nA_R}\left[\frac{1}{(1-m/n)} - 1\right] = \rho V_R Q\left[\frac{1}{(1-m/n)} - 1\right] \tag{14}$$

Eq 12 indicates that the pinning force on the clogging block is solely dominated by the change in the flow momentum force, $\rho V_R Q$. As illustrated in Figure 3, the force on the clogging block exponentially increases as m/n increases. It implies that the larger the rack surface area, the less resultant pinning force acting on the block. As a common practice, the rack surface area is recommended to be at least four times the pipe opening area (USWDCM 2001). In practice, the common mistake is to assume that the total external force, $(F_R\ Sin@ + F_B\ Sin@ + F_W)$, acts on the trash rack. The magnitudes of flow momentum force in Eq's 11 and 14 are much less than the hydrostatic force that is mainly balanced by the reaction force from the wing walls.

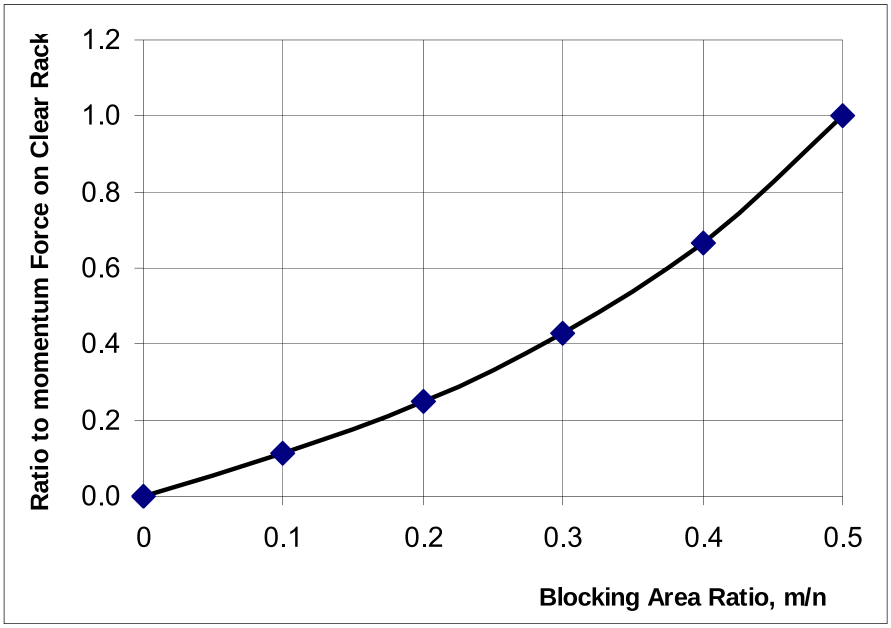

Figure 3 Force Acting on Block Landed on Rack Surface.

APPLCIATION TO FORENSIC STUDY

In a forensic study, it is frequent to ask how the pinning force acts on the clogging block, such a human body, on the rack. For instance, a 120-cm circular culvert is equipped with a trash rack that is laid on the FES. The opening area of the FES is 3.35 m^2. The inclined angle of the trash rack is 30 degrees relative to the streambed. During the storm event, the trash rack was partially clogged by a block that had a projected area of 0.32 m^2 on the rack surface area. As illustrated in Figure 4, the HGL and EGL through the system were analyzed using a flow rate of 3.2 cms. The headwater depth immediately upstream of the rack was 1.7 m and the hydraulic head immediately downstream of the culvert entrance was 1.26 m.

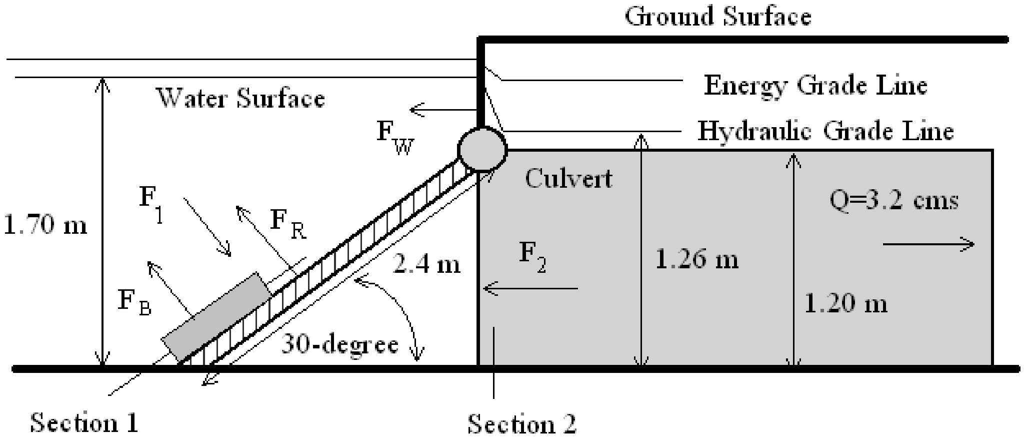

Figure 4 Flow Condition for Force Analysis

To quantify the pinning force, the method of superposition begins with the base condition, i.e. no trash rack on the FES, as:

$$A_1 = A_R = 3.35\, m^2$$

$$V_1 = \frac{Q}{A_R} = \frac{3.20}{3.35} = 0.96\, m/s$$

$$A_2 = \frac{\pi D^2}{4} = \frac{\pi (1.2)^2}{4} = 1.13\, m^2$$

$$V_2 = \frac{4Q}{\pi D^2} = \frac{4 \times 3.20}{\pi (1.2)^2} = 2.83\ m\ /\ s$$

$$\overline{Y_1} = Y_1 - \frac{L_R}{2} Sin@ = 1.70 - \frac{2.40}{2} Sin30^0 = 1.10\, m$$

$$\overline{Y_2} = Y_2 - \frac{D}{2} = 1.26 - \frac{1.20}{2} = 0.66\, m$$

$$F_1 = \gamma \overline{Y_1} A_1 + \rho Q V_1 = 9.8 \times 1.10 \times 3.35 + 1.0 \times 3.2 \times 0.96 = 39.13\, kN$$

$$F_2 = \gamma \overline{Y_2} A_2 + \rho Q V_2 = 9.8 \times 0.66 \times 1.13 + 1.0 \times 3.2 \times 2.83 = 16.33\, kN$$

F_B = F_R =0 for the base condition. Substituting the values of F_1 and F_2 into Eq 1 yields

$$F_W = F_1 Sin@ - F_2 = 39.13 Sin30^0 - 16.33 = 3.23\, kN\ or\ 727.\ lbs$$

The force, F_w. is the reaction force from the wing wall. Having the trash rack installed, the area opening ratio for the rack is 0.77 or 23% of the rack surface area is occupied by steel bars. The flow velocity through the rack is

$$V_1 = V_R = \frac{Q}{nA_R} = \frac{3.20}{0.77 \times 3.35} = 1.24\, m/s$$

$$F_1 = \gamma \overline{Y_1} A_1 + \rho Q V_1 = 9.8 \times 1.10 \times 3.35 + 1.0 \times 3.2 \times 1.24 = 40.05\, kN$$

The force, F_2, remains the same as without a rack. Under the clear rack condition, Eq 1 is solved as:

$$F_W + F_R Sin@ = F_1 Sin@ - F_2 = 40.05 Sin30^0 - 16.33 = 3.69\, kN\ or\ 830\ lbs$$

The force on the trash rack is found to be: F_R = 0.92 kN that is equal to 23% of the flow momentum through the clear rack. Of course, this force can be directly calculated using Eq 11 as:

$$F_R = \rho \frac{Q^2}{nA_R}(1-n) = 1.0 \times \frac{3.20^2}{0.77 \times 3.35} \times [1 - 0.77] = 0.91\, kN\ or\ 205\ lbs$$

Next, the clogging block is landed on the trash rack. As aforementioned, the additional blocking area on the rack is 0.32 m^2 or m=0.096. Applying Eq 13 to the blocked rack, the flow velocity is calculated as:

$$V_1 = V_B = \frac{Q}{A_R(n-m)} = \frac{3.20}{3.35 \times (0.77 - 0.096)} = 1.42\ m/s$$

Substituting the flow velocity at Section 1 into Eq 2 yields:

$$F_1 = \gamma \overline{Y_1} A_1 + \rho Q V_1 = 9.8 \times 1.10 \times 3.35 + 1.0 \times 3.2 \times 1.42 = 40.60\ kN$$

The difference between F_1 and F_2 represents the total external force as:

$$F_W + F_R Sin@ + F_B Sin@ = F_1 Sin@ - F_2 = 40.60 Sin30^0 - 16.33 = 3.97\ kN\ or\ 893\ lbs$$

The pinning force, F_B, on the block is found to be 0.56 kN that is 14% of the flow momentum force through the clear rack as shown in Figure 3. Of course, this force can be directly calculated using Eq 14 as:

$$F_B = \rho \frac{Q^2}{nA_R}[\frac{1}{(1-m/n)} - 1] = 1.0 \times \frac{3.20^2}{0.77 \times 3.35}[\frac{1}{(1-0.096/0.77)} - 1] = 0.56\ kN\ or\ 125\ lbs$$

In this case study, the reaction force from the wing walls is as high as 3.23 kN or 727 pounds in the flow direction. This reaction force is essentially resulted from the hydrostatic force due to the headwater at the culvert entrance. The pinning force on the clear trash rack is 0.91 kN or 205 pounds perpendicular to the rack surface. With a plugged area of 9.6%, the pinning force on the block is 0.56 kN 125 lbs perpendicular to the rack surface. The trash rack is submerged in the water flow. Consequently, the pinning force on the rack is mainly resulted from the flow momentum force due to the change in the flow velocity.

CONCLUSION

(1) This paper presents a new methodology to analyze the flow momentum force at a culvert entrance. With a trash rack on the flare-end section, the external forces on the flow control volume consist of the reaction force from the wing walls, and the pinning forces on the trash rack with and without blockage. To solve three unknown forces, the method of superposition was developed and illustrated by a forensic case.

(2) Without the superposition process, the conventional momentum principle provides the total external force that appears to be the pinning force on the trash rack. In fact, the hydrostatic force representing the water body weight is mainly balanced by the reaction force from the wing walls. The case study indicates that the pinning force on the submerged rack is only related to the flow momentum force that is much smaller than the hydrostatic force.

(3) The approach derived in this study is limited to the steady flow condition or the blockage on the rack is not so severe as to reduce the flow through the system. This approach is applicable to approximate the pinning force acting on a person or small animal that is washed against the trash rack. A pinning force is the normal force perpendicular to the rack surface. The effort to release a person from being pinned on the trash rack surface is not to overcome the pinning force itself. Rather, it is to overcome the friction force along the rack surface or a friction coefficient needs to be considered.

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APPENDIX II

A=flow area
A_B = blocked area on rack
A_R = cross sectional area at FES
D= culvert diameter or height
F = force acting on water,
F_W = reaction force from wing walls
F_R = contraction force through rack
F_B = pinning force on block,
L_R = length of trash rack on FES
m = blocked area ratio to rack surface area
n = area opening ratio of rack surface area
Q= flow in pipe
V = cross sectional average velocity
V_B = flow velocity through blocked rack
V_R = flow velocity through clear rack
Y = HGL relative to the culvert invert
$\overline{Y}$ = depth to centroid of flow area,
ρ = water density,
$\rho V_R Q$ = flow momentum force
@= inclined angle of rack.
γ = water specific weight

The subscripts, 1 and 2, represent the variables of Sections 1 and 2.