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MODEL STUDY OF A CULVERT SAFETY GRATING - SOUTH 4TH AND BROOKDALE STREETS, ALLENTOWN, PA

by

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I. Introduction

In recent years in the Lehigh Valley and elsewhere, accidents involving drainage structures have caused injury and death to people. Typically, these people have fallen into a drainageway obscured by flow over the banks, and have been swept downstream and into a drainage structure, such as a culvert.

Although some culverts do have gratings upstream, the purpose of such devices has been debris control. The design of debris control structures is documented in publications by Reihsen and Harrison(5) and California Division of Highways(2). Because debris control structures are designed to catch debris, i.e. the debris is pinned to the structure by the flow, such structures are not appropriate as safety devices.

A literature search reveals that little attention has been given to the problem of safety at drainage structures in the past. An exception to this is the study of the task force of Metropolitan Toronto, Canada(4), established to make recommendations concerning the design of safety gratings at culvert inlets. This group asked the National Water Research Institute of Environment Canada to perform a study and make design recommendations. The resulting study by Engel and Lau(1) used a culvert with various inlet grate configurations.

The design problem as recognized by Engel and Lau[1] is to provide a grating that will stop a person from being swept into the inlet and is oriented and positioned to allow the person to easily climb out of the waterway. To accomplish this, the grating must begin upstream of the region of intense acceleration of flow into the culvert where the pinning forces would be relatively small, Fig. 1. Also, the grating must be curved to avoid pinning and to allow a person to climb out of the flow. Their study involved measuring the force required to remove an object from the grating face. The smaller the pinning force, the more likely that a person would be able to extricate him/herself. Engel and Lau make the following conclusions and recommendations:

(a) Vertical grates used for debris control are hazardous because the accelerating flow can keep a person pinned to the grate.

(b) A grate should be sloped and placed upstream of the sharply accelerating region of flow.

(c) When the upstream channel width, B, exceeds the culvert width, b (or diameter, D), the grating is safer than when $B \simeq b$, Fig. 2.

(d) Specific design recommendations are offered for a grating curved in a parabolic manner in both the vertical and horizontal planes.

The report by Engel and Lau[1] was adapted and used by the Metropolitan Task Force on Storm Sewer Inlet Grating Design[4] to design a grating for a specific culvert in suburban Toronto. Because of fabrication problems, the grating used was parabolic only in the vertical plane, as shown in Fig. 1.

The purpose of this study is to apply the design recommendations in the literature[1],[4] to the culvert at South 4th and Brookdale Streets in Allentown, PA. This culvert passes Trout Creek under a broad intersection and is approximately 850' long. The culvert is 15' wide and has a bottom with a circular arc, giving a height of 5.5' at the center and 5.0' at each edge, Photo 1.

According to the FEMA Flood Insurance Study[3], the fifty-year return period flood exceeds the carrying capacity of the culvert and the roadway is overtopped. This provides a complication for flow at the culvert entrance not considered by Engel and Lau[1]. Although they did consider a submerged culvert entrance, Engel and Lau did not allow for flow over the roadway. Hence, the nature of the flow for this situation and the effectiveness of the parabolic shaped grating were not assessed and are addressed in this study.

The existing culvert, Photo 1, has 75^{o} wing walls at either side which slope downward. Because of the problems of designing a grating that would tie into these wing walls, it was decided by the engineering staff of the City of Allentown to re-design the inlet to the culvert using a head wall and 90^{o} wing walls giving a rectangular cross-section. The upstream reach of Trout Creek has a trapezoidal cross-section with a bottom width of 20', side slopes of approximately 1:1, and a depth of 10'. Hence, at a bank full stage, the cross-sectional area is approximately 300 ft^2. For the proposed new rectangular approach section to have a cross-sectional area of 300 ft^2, the width must be 30'. In Fig. 2, then, the culvert width is 15' and the distance, B, between wing walls is 30'. The wing walls will extend several feet upstream past the grating for a total length of 20'. Finally, a transition from the trapezoidal to rectangular cross-section must be constructed.

This study utilizes a physical model which includes an approach reach of Trout Creek and the re-designed inlet to the culvert. A range of flows were studied, including flows that do not submerge the inlet to flows that overtop the roadway, to assess the performance of the grating under a wide range of conditions. Flows in excess of the maximum capacity of the culvert, which overtop the roadway, are of special interest because they were ignored by Engel and Lau(1).

II. Model Design and Construction

The model was constructed in a tank with dimensions 10' wide, 30' long, and 2' deep, Photo 2, with a scale ratio of 1:10. The 5.5' x 15' prototype culvert is 6.6" high and 18" wide in the model. Using the Froude modeling law, the ten-year return period flow of 1080 cfs prototype flow is modeled by a 3.16 cfs flow.

A short reach of the approach bend of Trout Creek upstream of the culvert was modeled to establish the flow before reaching the culvert. The whole length of the culvert was not modeled. The flow vs. headwater condition at the culvert inlet was regulated with a tailgate. The FEMA Flood Study(3) gives a head water elevation of 329.25 feet for a flow of 1080 cfs. However, this set of head-flow rate values pertains to the existing inlet conditions as shown in Photo 1. For the proposed new head wall and 90^{o} wing walls, the flow vs headwater relationship is not known. However, the results of the study do not critically depend on the exact nature of this relationship. The assumption was made that the head-flow rate relationship with the new inlet will be similar to that with the existing inlet.

The stream reach was modeled using pea gravel capped with mortar. The model culvert was constructed of plywood. The model grating, Photo 3, was constructed from 0.11" re-bars. This size corresponds to a prototype bar of 1.1".

A total of 96 bars were used in the 3' model channel width, giving a bar-to-bar distance of 0.375" in the model (3.75" in the prototype). This is a conservative design; the bars could be smaller in diameter and the spacing could be larger. The Metropolitan Toronto[4] report recommends 3/4" to 1" bars spaced 4" to 5" apart.

Using the Metropolitan Toronto[4] design guidelines, the bars were bent into a parabolic shape according to the equation

$$y = \sqrt{2hx}$$

where h equals four-tenths of the culvert height, Fig. (1). An additional horizontal distance of bar of 4.8" extends to the ledge of the head wall. Engel and Lau[1] and Metropolitan Toronto[4] recommend that a ledge extend out from the head wall to allow a person to step off the grating, Fig. 1. Once bent into shape, the bars were cut 1.0" above the bottom (10" in the prototype). A horizontal bar extends across the channel at this level with supports at the third points. A second bar was positioned at a location half-way to the end of the bars. Finally, the horizontal segments of the bars tie into the mid-point of the ledge.

III. Testing and Results

The basic testing consisted of running a series of flows through the channel-culvert system with the grating in place and observing (i) the motion of the water through the grating and into the culvert and (ii) the motion of objects thrown into the channel and noting their interaction with the grating. A videotape was made to document both flow patterns and the motion of objects and has been submitted separately.

To assess the effect of the grating on the discharge-headwater relationship, the grating was removed as the last part of the testing program and water levels were measured at the same discharges used to assess the grating.

A. Flow Characteristics

1. Head-Discharge Relationship

There is a concern that the grating could change the head-discharge relationship; that is, with the grating in place, a higher head may be required to pass a given discharge. This occurs because the grating is an impediment to the flow. The table on the next page shows values of flow rate and corresponding water surface elevations taken with and without the grating just upstream of the culvert at location A shown in Fig. 1. It is expected that the change in water surface elevation, column 4 in the table on the next page, would increase with increasing discharge. That is the general trend. At high flows, the water surface contains waves

Prototype Flow (cfs)	Elevation (ft) Without Grating	With Grating	Change (ft)
300	327.52	327.62	+0.10
500	328.49	328.71	+0.22
600	328.93	329.35	+0.42
900	331.33	331.40	+0.07
1080	332.24	332.77	+0.53

and other disturbances, making measurements quite difficult. However, the changes measured are not very significant, and all are below 1.0'. For flows greater than the capacity of the culvert, where the water flows over the roadway, the influence of the grating is negligible.

The spacing of bars used in this study is less than that recommended in the Toronto Report. A wider spacing with smaller bars would cause even smaller increases in water surface elevation.

2. Flow Patterns

The approach flow to the culvert inlet was uniform across the channel. Whether the flow in the prototype is similarly uniform or whether there is a large separation zone on one side, typical of flow around bends, has not been assessed. For the purposes of this study, it seemed appropriate to use a uniform approach flow.

At all flows, the water in the center of the channel accelerates into the culvert inlet, while the flow along the banks slows as it approaches the head wall and merges into the opening.

At high flows in which the headwater depth exceeds the culvert height (submerged inlet), vortices formed at the corners where the wing walls meet the head wall (Photo 4). These vortices appear and dissipate periodically, and typically alternate from one side to the other. The presence of the grate has no effect on the occurrence of vortices.

An attempt to eliminate this problem was made by increasing the length of the ledge from 2.4" (2.0' prototype scale) to 7.0" (5'10" prototype scale). This extension eliminated the horizontal portion of the grating. However, the extension did not eliminate the vortices.

With a flow large enough to overtop the roadway, the vortices became larger, longer-lived, and persist on both sides of the channel.

B. Safety Aspects of the Grating

Assessing the safety aspects of the model grating is subjective, based on inferences about the flow pattern and the behavior of neutrally buoyant "human-shaped" objects placed in the channel. Several pieces of 1" diameter wooden dowel were used to simulate the motion of a person in the flow. Steel wire was wrapped around a dowel to weight it so that, in quiescent water, the dowel floated vertically with a small portion of its 5"-6" length above the water surface.

The motion of a dowel tossed into the channel depends on the flow in the channel. Basically, three situations were identified:

(i) Low, shallow flows.

With depths in the channel of 2.5' (prototype depth) or less, the dowel (5' long in prototype scale) drags along the channel. These flows are associated with frequent floods, those occurring several times a year. The flow itself is relatively tranquil. This situation is certainly less dangerous than higher flows for adolescents and adults because they would be able to stand in this flow and withstand the forces of the current.

Upon reaching the grating, the dowel turns on its side as shown in Fig. 3 and Photo 5. Because of the low angle of the grating to the flow direction, the flow pushes the dowel up the grating. This phenomena occurs irrespective of how the dowel approaches the grating, either along the channel sides or in the middle.

(ii) Moderate floods

With depths in the channel of 2.5' to 5.5', the flow in the channel and through the grating is quite turbulent and strong. Flood frequencies that cause such depths range from the 1 to 5 year events. These flows do not submerge the culvert inlet.

The motion of the dowel is identical to that experienced for shallow flows and depicted in Fig. 3 and Photo 5. Here, the angle between the flow and the grating is very low, approaching zero (where the grating is horizontal). The dowel is flipped sideways by the force of the flow and pushed up the grating. Unless badly injured, a person could easily roll or climb to the ledge and roadway.

(iii) Large floods

Flows that just submerge the inlet have approximately a 5-year return period. The FEMA study for Trout Creek gives the 10-year flood water surface elevation as 329.25' just upstream of the inlet. The top of the culvert is at an elevation of 328.7'. The roadway elevation is 333' and the FEMA study shows flow over the roadway for return periods of approximately 50-years and greater.

At high flows, the behavior of the dowel depends on whether it approaches the grating in the center of the channel or near the sides. If it approaches from the side, the dowel is pushed over the grating and is caught in the swirl or vortex at the corner. When the depths are small on top of the ledge (1' to 2'), this situation is probably not dangerous for adolescents and adults, because they could extricate themselves from the flow.

When the depths exceed the roadway elevation, the vortices persist and the situation is quite dangerous. The vortices are quite strong and turbulent in depths above the ledge equal to 3' to

5'. Of course, such depths would occur for very rare floods, 100-year return period and greater.

The diameters of the vortices shown in Photo 4 are 6'-10' across at the water surface. The higher velocity core or center is smaller, perhaps 2'-3' across. The regions of vortex formation could be protected or fenced off in some fashion so that a person would not be caught in the vortex. This aspect was not part of the scope of this study.

When the dowel approaches the grating in the center of the channel, the dowel flows over the grating to the ledge. When the depth over the ledge is small (0' - 2'), the dowel was pressed into the point marked "B" in Fig. 1. This potentially dangerous situation is easily rectified by joining the grating to the ledge near the very top of the ledge. For larger depths, the dowel is transported onto the roadway or is swept to the side into a vortex.

CONCLUSIONS

The grating design used in this study with the re-designed inlet conditions for the culvert at 4th and Brookdale performed satisfactorily. The grating itself provides little impediment to the flow and it satisfies its mission of both preventing human-scale objects from being carried into the culvert and preventing such objects from being pinned against the grating. Under no circumstances did the grating appear to contribute to a hazardous condition by causing a dangerous flow condition.

Some specific recommendations follow:

(i) The recommended grating dimensions are shown in Fig. 1.

(ii) While the size and spacing of bar used in the study caused only a small impediment to the flow, the bar size could be reduced and the spacing increased. A 3/4" to 1" bar spaced 4" to 5" apart is probably sufficient.

(iii) For flows up to approximately the 25-year flood, the grating will provide a beneficial safety function.

(iv) For larger, rarer flows that overtop the roadway, a person in the channel would most likely be swept over the culvert inlet and grating.

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Mr. Leidy Dittbrenner constructed the model culvert and grating. Mr. Jerome Madden helped with all phases of the model construction and testing. Mrs. Catherine Miller typed this report.

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2. California Division of Highways, California Culvert Practice, 2nd Edition.
3. Federal Emergency Management Agency, Flood Insurance Study, City of Allentown, PA, December, 1981.
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FIGURES

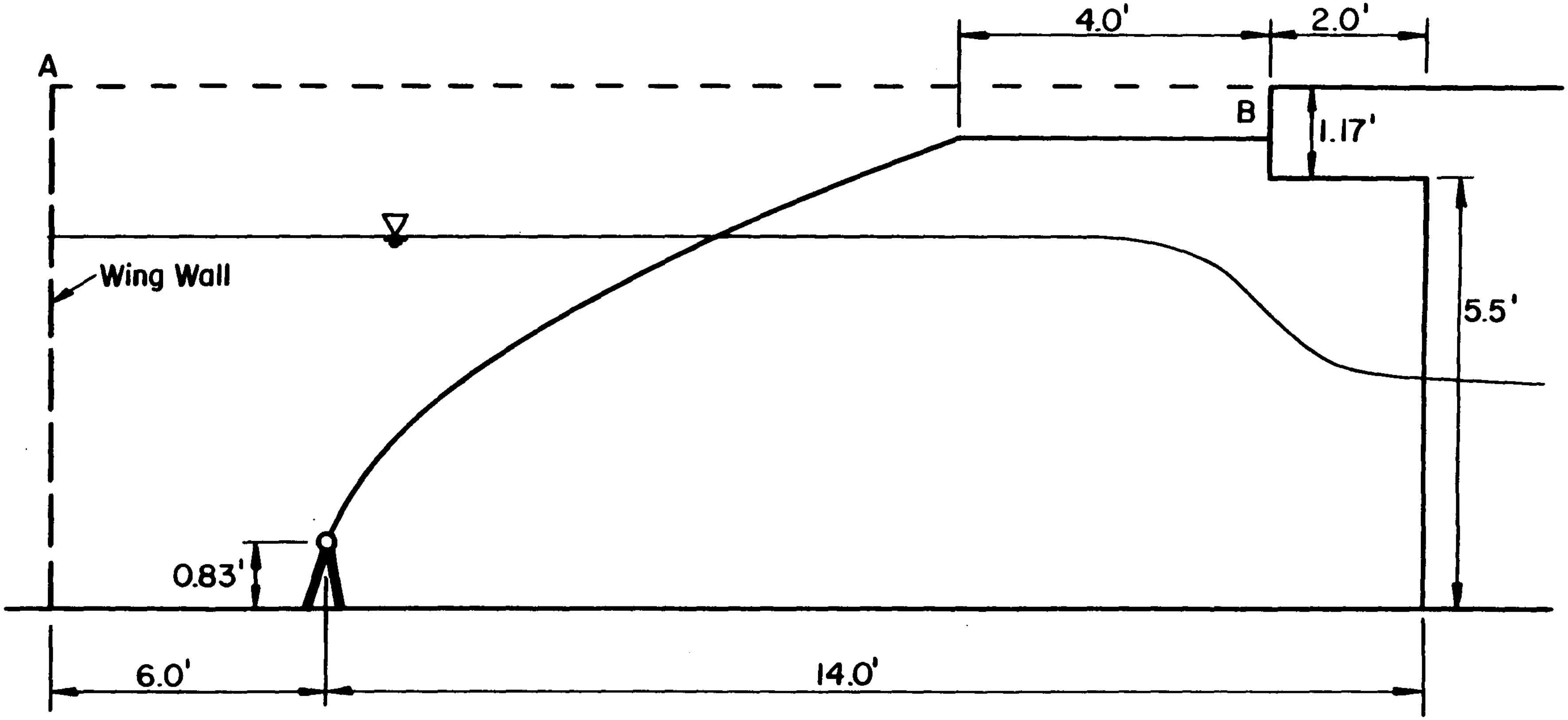

Figure 1: Elevation view of the proposed culvert inlet and grating.

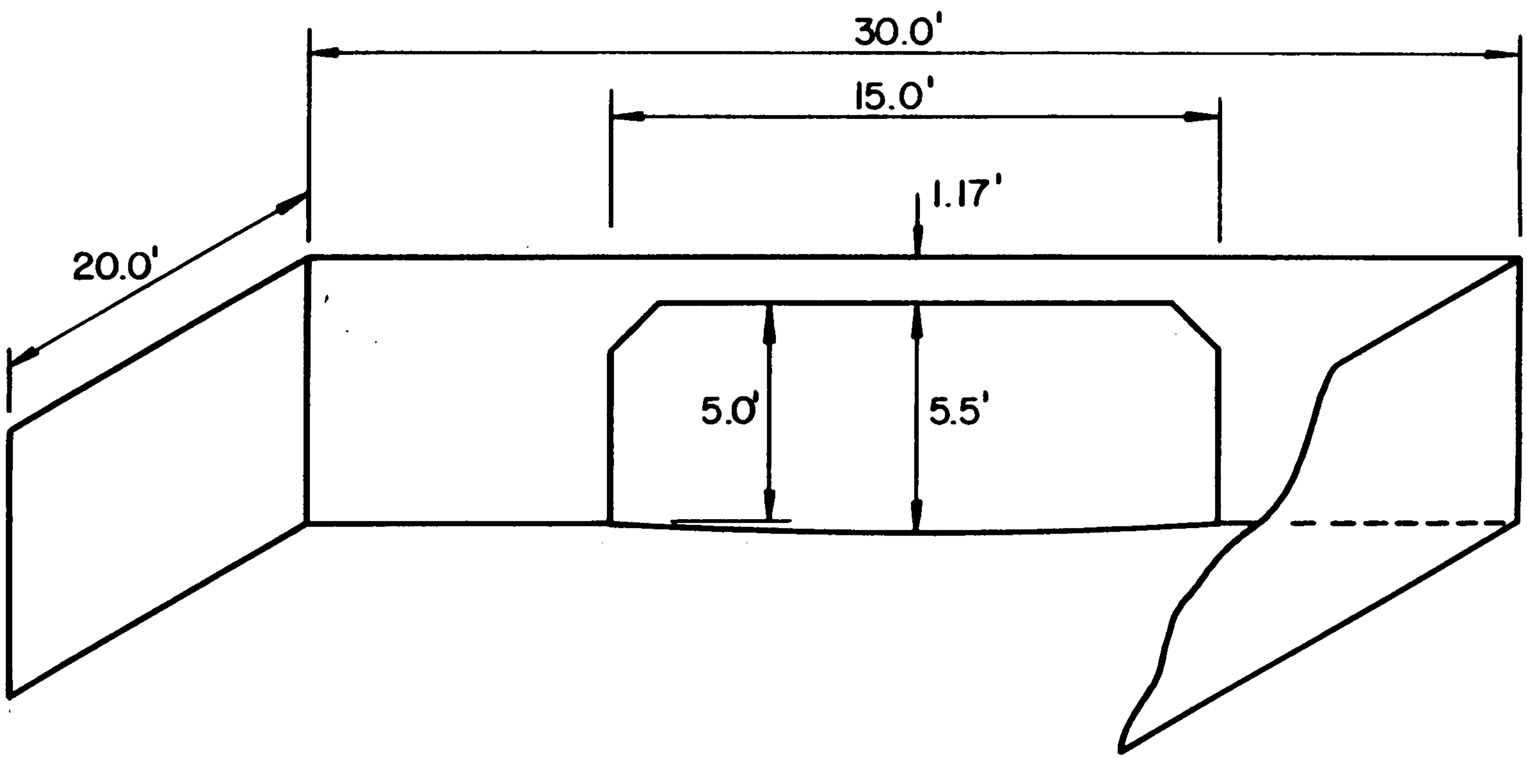

Figure 2: The proposed culvert inlet showing dimensions of the head wall and wing wall. The ledge and grating are not shown.

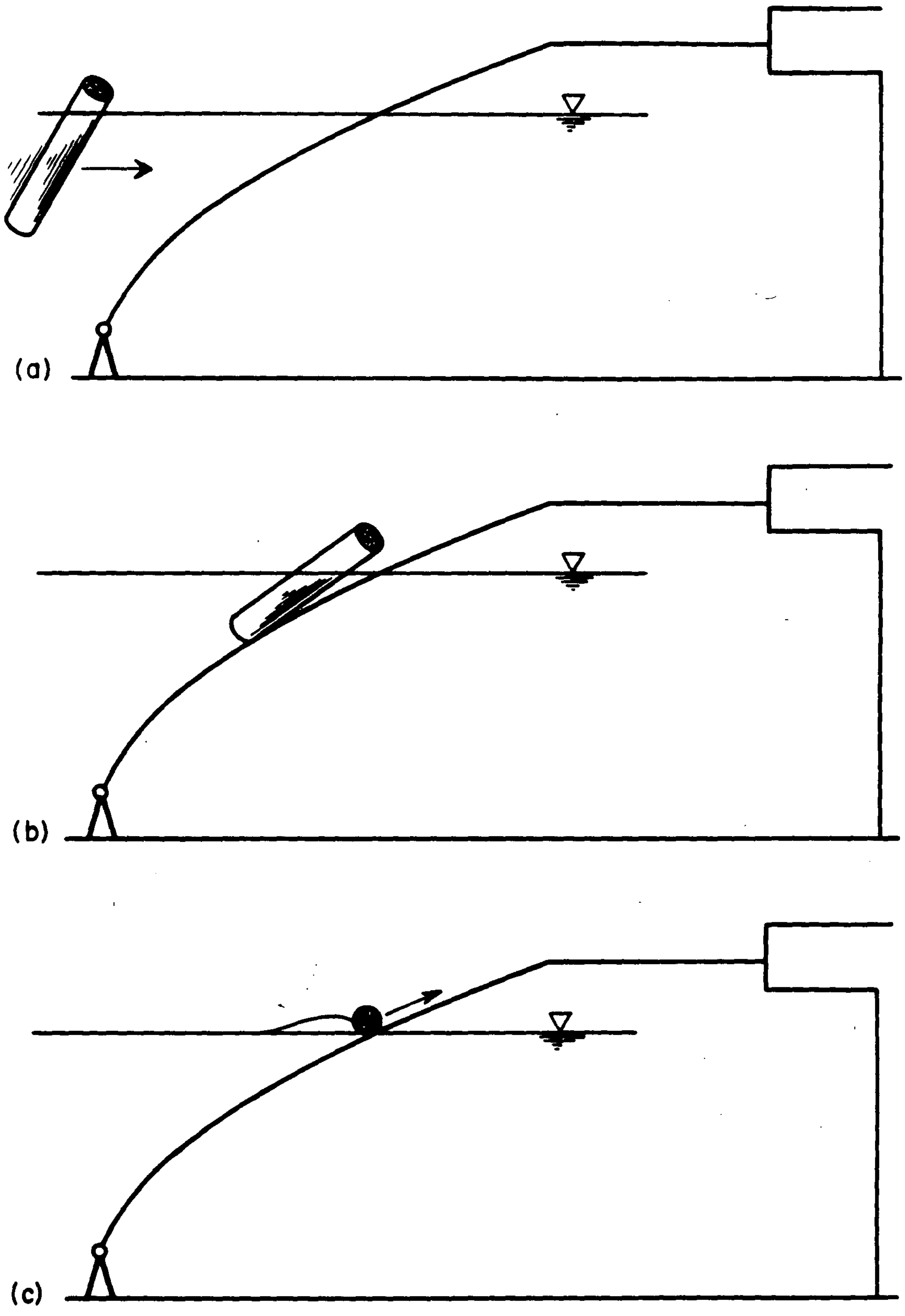

Figure 3: Schematic sketch of the motion of a dowel (a) moving down the channel, (b) turning at the grating, and (c) being kept horizontal on the grating.

PHOTOGRAPHS

Photo 1: The existing culvert inlet showing the approach reach of Trout Creek.

Photo 2: Overall view of modeling tank including channel reach and culvert inlet.

Photo 3: Close-up of the model grating.

Photo 4: Vortices at the corners of the intake.

Photo 5: The final position of the dowel after being carried down the channel.