Chapter 12

Energy Losses in a Tangential Helicoidal-Ramp Inlet for Dropstructures

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The results of a series of experiments that relate the piezometric head in the inflow pipe to the discharge are used to derive an empirical relationship for the energy loss coefficient for a tangential helicoidal-ramp inlet for vortex-flow dropstructures. The energy loss coefficient in the closed-conduit flow regime was found to decrease exponentially with the ratio of the hydraulic diameter of the ramp to the diameter of the inflow pipe.

12.1 Introduction

Due to rapid growth and urbanization of most of the major cities in the world, the capacities of their wastewater systems often are no longer adequate to handle the large volumes of wastewater discharged from houses and factories and from surface runoff during large storms. The resulting overflows of stormwater and raw sewage create a host of problems. Among them one can cite the blowout and loss of manhole or dropshaft covers in existing sewer systems (Yen, 1986) causing traffic delays. Overflows of sewer systems also cause flooding and pollution (Guo, 1991). A number of metropolitan cities use dropstructures to collect sewage and stormwater from surface to underground tunnel interceptors before conveying them to the wastewater treatment plants. These dropstructures also dissipate the energy associated with the fall.

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A review by Jain and Kennedy (1983) shows that dropstructures with a vortex-flow inlet are generally considered to be superior to those with a plunge-flow inlet. Existing vortex-flow inlets used in these types of dropstructures are constructed using an open cut construction. Site constraints governing the layout of the dropstructures may make an open cut construction very expensive, or even impossible. Consequently, there is a need for inlets that can be constructed using tunneling alone. Such inlets, termed radial and tangential helicoidal-ramp inlets, were recently developed by Jain et al. (1993). The hydraulic characteristics of the radial helicoidal-ramp inlet are described elsewhere (Ansar and Jain, 1996; Ansar, 1993). In this chapter, an empirical relationship for the coefficient of energy loss for tangential helicoidal-ramp inlets is developed from head-discharge measurements when the inflow pipe is flowing full.

12.2 Experiments

The experimental set-up of the dropstructure model is depicted in Figure 12.1. The main components of the model were the tangential helicoidal-ramp inlet, the dropshaft, the outflow pipe, the conveyance tunnel and the air measuring chamber. All model components, except the air-measuring chamber, were constructed of lucite to permit observation and recording of flow patterns. Most of the components were constructed in sections joined by flanges or metallic straps at their ends, so that modifications to the model could easily be made.

A schematic view of the tangential helicoidal-ramp inlet is shown in Figure 12.2. The inlet consists of an inlet conduit connected tangentially to a vertical dropshaft and a helicoidal ramp installed in the dropshaft. The helicoidal ramp was located at a predetermined distance below the invert of the inflow pipe. This ramp had a center circular hollow column through which some of the entrained air is vented. A three-revolution ramp was used in all runs. The ramp was made of steel and was painted to prevent rusting. Its characteristics (width, pitch, slope, etc.) varied from run to run. Its width and pitch varied respectively between 70 to 114 mm and 76 to 127 mm. A pair of screws, located such that they did not inhibit the incoming flow, were used to hold the ramp at the desired position. The ramp had a guide wall at its upper end to prevent spill of water over the ramp end. The diameter D_0 of the inlet conduit at its junction with the dropshaft can either be equal to, or larger than, the diameter D_1 of the inflow pipe. In the latter case, the inlet conduit has a sloping bottom which can be constructed easily in the field by filling with concrete the bottom region of the inlet tunnel. The diameter of the inflow pipe varied between 102 mm and 152 mm depending on the particular run. Its length was larger than ten times its diameter so that the flow at the entrance of the dropshaft was fully developed and well-established.

Figure 12.1 Schematic of the experimental set-up.

ELEVATION OF DROPSHAFT

SECTION A-A

Figure 12.2 Schematic of the tangential helicoidal-ramp inlet.

A flow-straightener section was installed at the upstream end of the inflow pipe to avoid secondary velocities and insure a smooth flow in the inflow pipe. A valve and a calibrated orifice meter were installed in the supply line upstream of the inflow pipe and were used to control and measure the discharge in the inlet section. The dropshaft was 292 mm in diameter in all runs and consisted of two or more sections of different lengths connected by bolted flanges at the ends of the sections. Its length was approximately 3.3 m. This vortex-type inlet induced an angular motion to the water as it entered the dropshaft causing a swirling flow before the water reached the ramp.

Flow to the model was supplied from a constant-head tank, and was measured by means of a calibrated orifice meter in the supply line, and a precision two-tube water manometer. The piezometric head in the inflow pipe was measured by means of a piezometer connected to a pressure tap at the bottom of the inflow pipe, about 1.4 m upstream of the junction of the inflow pipe and the dropshaft.

Each experiment consisted of establishing the desired discharge in the model, and then, after the flow became steady, measuring the piezometric head in the inflow pipe and observing the flow patterns.

12.3 Energy Loss Coefficient

The inlet configurations tested in the study are summarized in Table 12.1. Tests were conducted for two values of ramp pitch P , three values of ramp width W and six values of drop Z_1 . Z_1 is the distance between the invert of the inflow pipe and the top of the ramp.

Table 12.1 Tangential helicoidal-ramp inlet configurations.

Run	Diameter		Helical Channel						Remarks*
	Inflow pipe D_I (mm)	Inlet Conduit D_O (mm)	Pitch P (mm)	Width W (mm)	Slope ϕ (deg.)	Area (cm^2)	Distance Z (mm)	Drop Z_1 (mm)	
T1	152	152	127	70	10	87.6	508	127	NGW
T2	152	152	76	114	8	85.8	228	0	
T3	152	152	76	114	8	85.8	380	152	NGW
T4	152	152	127	95	12	118.0	381	0	
T5	152	152	127	95	12	118.0	483	102	NGW
T6	102	152	127	95	12	118.0	534	102	
T7	102	152	127	95	12	118.0	432	0	NGW
T8	152	152	127	95	12	118.0	483	102	

*NGW: No guide wall was used

The test results, depicted in Figure 12.3, present head-discharge curves for runs T1 through T8. A typical head-discharge curve comprises three flow regions (a critical-depth flow region, a transition flow region, and a closed-conduit flow region) and is depicted in Figure 12.4. In the critical-depth flow region the flow in the inflow pipe is controlled by the downstream section of the inlet conduit. The flow depth in the inflow pipe is close to critical in this region. In the transition flow region the flow is between the critical-depth flow regime driven by gravity (open channel flow) and the closed-conduit flow regime driven by pressure gradients. In this region the flow conditions at the downstream section of the inlet conduit are affected by the flow conditions in the ramp, which in turn affect the flow depth in the inflow pipe. In this range of discharges the helical channel was flowing with an air-water mixture. In the closed-conduit flow region both the inflow pipe and the helical channel flowed full, without air, like a closed conduit. The analysis for the results in the critical-depth flow region are reported elsewhere (Ansar 1993). The analysis for the results in the closed-conduit flow region is described below, with particular attention to the energy loss coefficient.

Figure 12.3 Head-discharge curves for the tangential helicoidal-ramp inlet.

In the closed-conduit flow region, the coefficient accounting for energy losses (essentially form losses) can be estimated from the energy equation. This equation, written between the section in the inlet pipe where the piezometric head measurements were taken and the exit of the ramp (Ansar and Jain, 1996; Ansar, 1993), is:

Figure 12.4 Typical head-discharge curve.

$$h + \frac{V_I^2}{2g} + Z = \frac{3}{2} \left(\frac{Q^2}{gW^2} \right)^{\frac{1}{3}} \cos \phi + f_p \frac{L_p}{D_I} \frac{V_I^2}{2g} + K \frac{V_I^2}{2g} \quad (12.1)$$

where:

- V_I = velocity of the flow at the inlet section;
- Z = distance between the invert of the inflow pipe and the bottom of the ramp;
- W = width of the flow at the exit of the ramp;
- ϕ = slope of the ramp;
- f_p = Darcy-Weisbach friction factor for the inflow pipe;
- L_p = length of the inflow pipe;
- K = energy loss coefficient;
- g = gravitational acceleration;
- h = piezometric head in the inflow pipe;
- D_I = inflow pipe diameter; and
- Q = discharge.

The three terms on the left hand side of Equation 12.1 together represent the total head at the inlet section. The first term on the right hand side is the total head at the critical depth in a rectangular channel of width and slope the same as those of the ramp. The flow at the exit of the ramp, which previously has been restrained by the ramp, is suddenly released in the form of an annular jet. Such a flow in an open channel is always critical at or near the point of release (Henderson, 1966).

It was therefore assumed that the total head at the exit of the ramp is equal to the total head at the critical depth. It should be noted that initially the total head at the exit was taken to be equal to the sum of the pressure and velocity heads at the exit of the ramp, and the pressure at the exit was assumed to be atmospheric. This initial attempt failed to yield a satisfactory correlation between the loss coefficient and the geometrical parameters of the inlet. The second term on the right hand side of Equation 12.1 accounts for frictional loss in the inlet pipe. The frictional loss in the ramp was neglected because the number of revolutions of the ramp did not affect the head-discharge relation (Ansar, 1993). The last term containing K accounts for the energy losses due to expansion as the flow enters the dropshaft and due to contraction as the flow enters the ramp. The friction factor f_p was obtained from the Moody diagram and the length of the inflow pipe L_p was 1.40 m. In each run the only unknown is K which is obtained from Equation 12.1. The values of the loss coefficient K , which were determined from the experimental data and Equation 12.1, are used to develop an empirical correlation between K and the geometrical parameters of the inlet.

The energy loss coefficient obtained from Equation 12.1 is plotted as a function of the ratio of the hydraulic diameter of the ramp to the inflow pipe diameter in Figure 12.5. This figure shows that the energy loss coefficient decreases as the hydraulic diameter of the ramp increases as expected. In this figure the curve representing the energy loss coefficient can be described by the following relation:

$$K = 96.6 \exp\left(-2.59 \frac{D_h}{D_i}\right) \quad (12.2)$$

where D_h is the hydraulic diameter of the ramp, given by:

$$D_h = \frac{4WP \cos \phi}{P \cos \phi + 2W} \quad (12.3)$$

and, P is the pitch of the ramp, as shown in Figure 12.2.

Equation 12.2 fitted the experimental data with an accuracy of -12.1% to +7.4%.

The inlet configurations in all tests were such that the flow goes through an expansion as water enters the dropshaft, and then a contraction as it flows through the helical channel. The energy losses in the inlet can therefore be expected to behave similarly to those in a circular pipe that suddenly expands and then suddenly contracts. For both sudden expansion and sudden contraction in circular pipes, the energy loss coefficient decreases with increasing diameter ratios (diameter of the smaller pipe over the diameter of the bigger pipe) (White, 1986). A similar pattern is observed with the energy loss coefficient for the tangential helicoidal-ramp inlet as shown in Figure 12.5.

Figure 12.5 Energy loss coefficient for the tangential helicoidal-ramp inlet.

12.4 Conclusion

A vortex-flow inlet to dropstructures, called the tangential helicoidal-ramp inlet, was developed and tested in a laboratory study. This inlet can be constructed entirely by tunneling. An empirical relation for the energy loss coefficient for this inlet is derived from head-discharge measurements in the inflow pipe. The energy loss coefficient decreases exponentially with the ratio of the hydraulic diameter of the ramp to the diameter of the inflow pipe.

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Notation

D	dropshaft diameter (mm)
D_A	center column diameter (mm)
D_h	hydraulic diameter of the ramp (mm)
D_i	inflow pipe diameter (mm)
D_o	inlet conduit diameter (mm)
f_p	Darcy-Weisbach friction factor in the inflow pipe
g	gravitational acceleration (m/s^2)
h	flow depth in the inlet section, piezometric head (mm)
K	energy losses (form losses) coefficient
L_p	length of the inflow pipe (m)
n	number of revolutions of the helicoidal ramp
P	helicoidal ramp pitch (mm)
Q	discharge (m^3/s)
V_i	velocity of the flow at the inlet section (m/s)
W	helicoidal ramp width (mm)
Z	distance between the invert of the inflow pipe and the bottom of the ramp (mm)
Z_1	distance between the invert of the inflow pipe and the top of the ramp (mm)
ϕ	helicoidal ramp slope (degrees)

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