



# Hydraulic Losses in River Meanders

by Gary L. Brown,<sup>1</sup> Ronald R. Copeland,<sup>2</sup> and Craig Fischenich<sup>3</sup>

August 2007

## Complexity

Low	Moderate	High		

## Value as a Design Tool

Low	Moderate	High		

## Cost

Low	Moderate	High		

## OVERVIEW

Energy losses along a channel reach occur from friction along the channel boundaries and bed surface and channel irregularities, obstructions, vegetation, channel meandering, and many other parameters of lesser importance. Conventional application of hydraulic computations between two cross sections requires that these losses be represented by the application of a resistance or roughness coefficient. These coefficients are determined empirically. Although much research has been expended developing relations for resistance due to grain size, bed form, and vegetation, relatively little research has focused on the influence of channel meanders. This shortcoming has implications in stream restoration practice for urban channels because many designs include sinuous channels in areas where flooding impacts must be assessed.

This technical note discusses and analyzes several methods to estimate the hydraulic loss induced by river meanders (hereafter referred to as meander losses). These methods may be used to adjust the channel Manning's roughness coefficient used in hydraulic calculations and in numerical models such as HEC-RAS, HEC-2 and HEC-6. A method is recommended, with

conditions, and topics of further study are suggested in this technical note.

## RELEVANT PARAMETERS

The hydraulic parameters relevant to meander losses can be determined by dimensional analysis. Using such an analysis, Onishi, Subhash, and Kennedy (1976) found the following parameters to be significant:

$$n_b = f \left( \frac{U}{\sqrt{gR}}, \frac{R}{d_{50}}, \frac{B}{r_c} \right) \quad (1)$$

where

- $n_b$  = meander loss (expressed in terms of Manning's  $n$ )
- $U$  = mean velocity
- $G$  = acceleration due to gravitation
- $R$  = hydraulic radius
- $d_{50}$  = median grain size
- $B$  = channel width
- $r_c$  = radius of curvature of the meander

$U/(\sqrt{gR})^{1/2}$  (the Froude number) is hereafter given as  $Fr$ .

Onishi, Subhash, and Kennedy (1976) further concluded that meander losses are primarily associated with four separate phenomena. The first is *boundary shear*,

<sup>1</sup> U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

<sup>2</sup> U.S. Army Engineer District, Vicksburg, Vicksburg, MS.

<sup>3</sup> U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

which is associated with secondary currents and boundary deformation through the meander. The second is *superelevation of the water surface*, which alters the hydraulic radius and the pressure distribution through the bend. The third is *bed form drag*, which results from a change in bed form characteristics through the meander. The fourth phenomenon is *form drag*, which results from flow separation at the point bar and induces a reduction in the effective cross-sectional area of the channel. Form drag losses are typically associated with either a high Froude number flow or flow through tight meanders.

## LABORATORY DATA

Two sets of laboratory data were used to evaluate several different methods of estimating meander losses. The Science and Engineering Research Council Flood Channel Facility (SERC FCF) at HR Wallingford in the United Kingdom (U.K.) collected flume data for several different flow conditions and flume geometries. The data selected for this analysis were taken from flume geometries that were designed to simulate natural river morphology (i.e., a channel thalweg along the outer bank of the meander and a point bar along the inner bank). Two flumes in the set of SERC FCF experiments satisfied this criterion: One with meander half-angles of 60° and the other with meander half-angles of 110°. Both flumes were constructed with smooth boundaries with turbulent smooth flow. Additional experiments were conducted at the Iowa Institute of Hydraulics Research (IIHR) (Onishi et al. 1976). For each of these experiments, the following procedure was followed: A rectangular, meandering flume was filled with sand, and flow was passed through the flume until the bed geometry came to equilibrium. Hence, a natural meandering river geometry was established. Two separate experiments were conducted, one with a full-width flume and another with a half-width flume that was created by inserting an impermeable

partition along the centerline of the full width channel. The meander half-angle for both of these experiments was 45 deg. The boundary was rough with turbulent rough flow.

## ANALYSIS

Data from the SERC-FCF and IIHR flumes were used to evaluate several methods of predicting hydraulic losses in meanders. The methods evaluated in this analysis are Soil Conservation Service (SCS) (1963), Linearized Soil Conservation Service (LSCS), Mockmore (1944), Leopold et al. (1960), Argawal et al. (1984), Toebe and Sooky (1967), Pacheco-Ceballos (1983), and Cowan (1956). The SCS (1963) and Cowan (1965) methods are identical with respect to meander loss criteria and are given as a discontinuous function of sinuosity P. The Cowan method is described in more detail in EM 1110-2-1601 (U.S. Army Corps of Engineers 1994). The LSCS method is simply the SCS formulation mapped onto a piecewise continuous function of P. Both Leopold et al. (1960) and Mockmore (1944) relate meander loss as a function of  $B/r_c$ . The method of Argawal et al. (1984) is given as a function of Reynolds number, bend angle, depth, channel width, radius of curvature, and Froude number.

The analysis was conducted in the same manner as the analysis done by James and Wark (1992). The results are presented in terms of the percent error in the meander loss estimation, which is expressed in terms of the ratio of the value of Manning's n associated with both friction losses and meander losses to the value of Manning's n associated with friction losses only ( $\eta$ ):

$$\eta = (n_b + n)/n \quad (2)$$

The percent error is found as follows:

$$\text{Error} = 100 * (\eta_p - \eta_m) / \eta_m \quad (3)$$

<b>Table 1. Results from the SERC-FCF Experiments</b>				
<b>Meander loss estimation methods (formulated in terms of an n ratio)</b>	<b>SERC, 60° Meander, natural cross-section</b>		<b>SERC, 110° Meander, natural cross-section</b>	
	<i>Average error (%)</i>	<i>Standard deviation of the error</i>	<i>Average error (%)</i>	<i>Standard deviation of the error</i>
SCS (1963)	-5.50	1.00	-8.98	0.70
LSCS	-4.75	1.00	14.54	0.88
Mockmore (1944)	-5.54	1.45	-13.79	0.87
<b>Leopold et al. (1960)</b>	<b>2.93</b>	<b>1.01</b>	<b>-0.59</b>	<b>0.80</b>
Argawal et al. (1984)	67.66	15.25	93.44	12.12
Toebees and Sooky (1967)	6.77	2.00	4.19	1.75
Pacheco-Ceballos (1983)	-14.78	1.38	-18.89	0.80
Cowan (1956)	-5.50	1.00	2.89	0.79

<b>Table 2. Results from the IIHR Experiments</b>				
<b>Meander loss estimation methods (formulated in terms of an n ratio)</b>	<b>Onishi et al., 45° Meander, Full Width</b>		<b>Onishi et al., 45° Meander, Half Width</b>	
	<i>Average error (%)</i>	<i>Standard deviation of the error</i>	<i>Average error (%)</i>	<i>Standard deviation of the error</i>
SCS (1963)	-6.77	10.86	-2.56	9.91
LSCS	0.08	11.66	4.60	10.63
Mockmore (1944)	9.18	13.86	7.05	12.23
<b>Leopold et al. (1960)</b>	<b>1.91</b>	<b>11.87</b>	<b>-2.56</b>	<b>9.91</b>
Argawal et al. (1984)	3.73	6.63	8.62	4.97
Toebees and Sooky (1967)	68.89	15.00	76.66	17.41
Pacheco-Ceballos (1983)	24.20	40.18	22.41	36.30
Cowan (1956)	-6.77	10.86	-2.56	9.91

where  $\eta_p$  is the predicted value of the  $n$  ratio, and  $\eta_m$  is the measured value of the  $n$  ratio. Tables 1 and 2 compare the prediction methods with the measured flume data.

Of the methods analyzed, Pacheco-Ceballos (1983) and Toebes and Sooky (1967) yield unsatisfactory results and are henceforth disregarded.

Of the remaining meander loss estimation methods, the method of Leopold et al. (1960) appears to yield the most satisfactory results. Since it is given as a function of  $B/r_c$ , it is preferable to the methods formulated as functions of only sinuosity for two reasons: (1) The use of  $B/r_c$  is corroborated by dimensional analysis; and (2) the data from Onishi et al. (1976) indicate that flumes with nearly identical sinuosities but different widths will have different values of meander loss (the mean value of  $\eta$  for the full width flume is 1.087, the mean value for the half-width flume is 1.036).

The method of Leopold et al. (1960) is taken from a linear regression of data presented in the paper. It is given as follows:

$$\eta = (2.632 B/r_c + 0.474)^{1/2} \quad \text{for } B/r_c \geq 0.2$$

$$\eta = 1 \quad \text{for } B/r_c < 0.2$$

This method is only valid for flows where form drag due to flow separation is not present. Flow separation can dramatically increase meander losses. As was noted earlier, flow separation is associated with flows at high Froude numbers and/or tight meanders. A regression expression that is useful for estimating the threshold for flow separation in a meander can be taken from data presented in Leopold et al. (1960). Flow separation is not expected to occur if the following condition is satisfied:

$$Fr < 0.4161 (B/r_c)^{-2.475} \quad (4)$$

Note that Equation 4 is generated from Froude numbers ranging between 0.4 and 0.61 and values of  $B/r_c$  ranging between 0.22 and 1.2. Hence, any application of Equation 4 to values outside these ranges should be made with caution.

## RESEARCH RECOMMENDATIONS

None of the data analyzed herein contain hydraulic losses due to flow separation in the bend; i.e., the criteria of Equation 4 are not violated. Of the available methods, only Argawal et al. (1984) appears to include the influence of flow separation. It is given as follows:

$$\eta = 2.16 (Re (\theta/180^\circ))^{-4.65} (B/d)^{1.11} (r_c/B)^{1.38} Fr^{9.29-0.042} \quad (5)$$

Although this method did not compare favorably with the SERC-FCF data, it merits further consideration in future studies, especially in experiments that include flow separation. Flume data that cover a wider range of Froude numbers and width- to radius-of-curvature ratios are needed to develop a predictive equation for meander losses over a wider range of flow conditions.

The IIHR data have advantages over the SERC-FCF data in that the flumes had a natural meander bed geometry and rough turbulent flow (both of which are characteristic of natural rivers). However, these data have the disadvantage of having significant data scatter (see the standard deviations given in Table 2). This is due not to some deficiency in the quality of the data, but rather to difficulties in calculating the bend loss estimates. (The focus of the study is sediment transport, and bend losses are merely a secondary goal of the analysis.) Therefore, another flume study, conducted in much the same manner as the IIHR study but with the specific goal of determining meander losses, would be helpful in evaluating existing and future estimates of meander losses.

## ACKNOWLEDGEMENTS

Research presented in this technical note was developed under the U.S. Army Corps of Engineers Ecosystem Management and Restoration Research Program. Technical reviews were provided by Jock Conyngham and Mike Channell, both from the ERDC Environmental Laboratory, Vicksburg, MS.

## POINTS OF CONTACT

For additional information, contact Gary Brown (601-634-4417, [gary.i.brown@erdc.usace.army.mil](mailto:gary.i.brown@erdc.usace.army.mil)), Dr. Craig Fischenich (601-634-3349, [craig.Fischenich@erdc.usace.army.mil](mailto:craig.Fischenich@erdc.usace.army.mil)), or the manager of the Ecosystem Management and Restoration Research Program, Glenn G. Rhett (601-634-3717, [glenn.g.rhett@erdc.usace.army.mil](mailto:glenn.g.rhett@erdc.usace.army.mil)). This technical note should be cited as follows:

Brown, G. L., R. R. Copeland, and C. Fischenich. 2007. *Hydraulic losses in river meanders. EMRRP Technical Notes Collection*. ERDC TN-EMRRP-SR-41. Vicksburg, MS: U.S. Army Engineer and Research Development Center. [www.wes.army.mil/el/emrrp](http://www.wes.army.mil/el/emrrp)

## REFERENCES

Argawal, V. C., R. J. Garde, and K. G. Ranga Raju. 1984. Resistance to flow and sediment transport in curved alluvial channels. In *Asian and Pacific Division, International Association of Hydraulics Research Congress Proceedings 4*, 207-218.

Cowan, W. L. 1956. Estimating hydraulic roughness. *Agricultural Engineering* 37(7): 474-475.

James, C. S., and J. B. Wark. 1992. *Conveyance estimation for meandering channels*. HR Wallingford Report SR 329, Wallingford, UK.

Leopold, L. B., R. A. Bagnold, M. G. Wolman, and L. M. Brush. 1960. *Flow resistance in sinuous or irregular channels*. USGS Professional Paper 282-D, Washington, DC.

Mockmore, C. A. 1944. Flow around bends in stable channels. *Transactions American Society of Civil Engineers* 109: 593-618.

Onishi, Y., C. J. Subhash, and J. F. Kennedy. 1976. Effects of meandering in alluvial streams. *Journal of the Hydraulics Division, American Society of Civil Engineers* 102(7): 899-917.

Pacheco-Ceballos, R. 1983. Energy losses and shear stresses in channel beds. *Journal of Hydraulic Engineering* 109(6): 881-896.

Soil Conservation Service (SCS). 1963. *Guide for selecting roughness coefficient 'n' values for channels*. Washington, DC: USDA Soil Conservation Services.

Toebe, G. H., and A. Sooky. 1967. Hydraulics of meandering rivers with floodplains. *Journal of Waterways and Harbors Division, American Society of Civil Engineers* 93(2): 213-236.

U.S. Army Corps of Engineers. 1994. *Engineering and Design – Hydraulic design of flood control channels*. Engineer Manual 1110-2-1601. Washington, DC.