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Modeling of Developed Meanders of an Alluvial Channel

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1. Introduction

The meandering planforms of alluvial rivers pose hazardous impacts on the human life, for a major portion of inhabitation lies on the banks of such rivers for the reason of easy water availability, land fertility and food grain productivity, and economic navigation and transportation of goods. Meandering is a self-induced plan deformation of a stream that is (ideally) periodic and anti-symmetrical with respect to an axis, which may or may not be exactly straight. According to this definition, which will be used in the following, an alluvial stream which deforms its initially straight channel into one of the periodic and anti-symmetrical plan forms is meandering; whereas a stream flowing in a tortuous rocky terrain or in a rigid sinuous flume, whose curvilinear plan pattern has not been created by that stream itself, is not meandering. Meandering can be classified as regular, irregular, or skewed, depending on the form of the meandering bend migration. The thalweg and tortuosity describe the meandering characteristics.

The most important parameter defining meander geometry is the tortuosity or sinuosity of the curved channel. Tortuosity was defined by Leopold and Wolman (1957) as the ratio of thalweg length (length along the line of maximum depth) to valley length, by Friedkin (1945) as the ratio of thalweg length to air line distance, and by Leopold and Wolman in their subsequent contribution (1960) as ratio of arc distance to wave length in a single meander. The first definition appears to be preferable because of its simplicity, requiring less judgement in measurement. To help visualize the degree of meandering associated with a particular tortuosity ratio, available concepts were examined. The concept which appeared most satisfactory was that presented by Langbein and Leopold (1966), who postulated that the planimetric geometry of a meander is that of a random walk, whose most frequent form is that which minimizes the sum of squares of the changes in direction, in each successive unit length. The direction angles are then sine functions of channel distance. This yields a meander shape typically present in meandering rivers.

Every phase of meandering represents a changing relationship between three closely related variables: the flow and the hydraulic properties of the channel, the amount of sand moving along the bed, and the rate of bank erosion. These three variables constantly strive to reach a balance, but never do even with a constant rate of flow. The bends of a meandering river have limited widths and lengths. The flow and the hydraulic properties of the meandering river, the amount of sand moving along the bed, and the rate of bank erosion determine these limits. When a bend reaches this width, a chute forms and a new bend develops farther downstream. Distorted bends and natural cut-offs are caused by local changes in the character of bank materials.

Several hypotheses have been brought forward to explain meandering. Meandering has been attributed to the earth's rotation; to the excessive slope and energy of a river (Anderson, 1967; Raudkivi, 1966, 1967; Fredsoe, 1982; McLean and Smith, 1986; Gust, 1988; Nelson, 1989; Yilmaz, 1990; and to changes in stage of sediment formation at the boundary (Exner, 1919). It is often considered that an irregularity in the bankline or another causing factors will disturb the flow and cause meandering. Alternate bars give rise to a sinuous migrating thalweg within initially straight banks, and might somehow evolve into meanders, provided channel banks are also erodible. The formation of alternate bars imply incipient meandering (Tubino and Seminara, 1990). The coexistence of free or migrating and forced or fixed bars in a meandering channel has been investigated through laboratory experiments by Gottlieb (1976) and Fujita and Muramoto (1982).

Rivers with a sinuosity, defined as the ratio of valley slope to channel slope, of 1.5 or greater are considered as meandering (Leopold and Wolman, 1957). In a simple of 50 rivers differing in size as well as in physiography, Leopold et al., 1964, found that two-thirds of the ratios were in the range 1.5-4.3, with a median value of 2.7. In view of this striking geometric regularity of winding rivers, they suggested that meanders are no accident and they appear to be in the form in which a river does the least work in turning. A river is the author of its own geometry. It is adjusted, in the long term, so that its ability to transport balances the water discharge and sediment load supplied from the watershed.The adjustments, which may include channel geometry, slope, meandering pattern, roughness, etc., reflect in part changes in the river's resistance; that is, in energy expenditure. It has previously been suggested that the basic reason for meandering is related to the rate of energy, or power, expenditure (Leopold and Wolman, 1960; Yang and Song, 1971). Meander geometry is obtained such that the inflow quantities of water and sediment are carried with minimum power expenditure per unit channel length as well as minimum power for the river reach. Chang (1979) applied the concept of minimum stream power per unit channel length together with relations of continuity, bed load, flow resistance, bank stability, etc., to obtain the regime geometry of alluvial streams under uniform flow conditions.

For a given discharge, meandering occurs on smaller slopes (Lane, 1957; Leopold and Wolman, 1957; Schumm, 1977). At steeper slopes, rivers are often braided in multiple channels separate by interlaced islands. In addition to the smaller slope and sinuous pattern, meandering rivers are characterized by a nearly uniform width along the channel. For purposes of river meander analysis (Chang, 1984), variables for regime conditions have been identified as independent variables, dependent variables, and constraints (Kennedy, and Brooks, 1963; Leopold, Wolman and Miller, 1964). Those which are imposed on the river from its watershed are independent variables or controlling variables and those which result when equilibrium is reached are dependent variables. Water discharge and sediment inflow and their respective properties which are determined by the watershed are independent variables for the river. Dependent variables include the flow velocity, channel width, flow depth, channel slope, and radius of curvature. The channel roughness and transverse bed slope in the curved channel are not additional dependent variables as they may be computed based on other variables. The valley slope is treated as another independent variable since the time scale for its formation is much greater than for regime channel geometry. The bank slope is another dependent variable.

The increased concern with riverbank erosion has increased the demand for theoretical models that can predict flow and bed features in a meandering alluvial channel. The most significant meander-flow characteristics are the spiraling of the mean flow due to channel curvature and nonuniformity of the velocity profile, the point bar, and deep pool bed topography near the apex of each bend. In order to plan, design, construct, or maintain bank-erosion control structures and river-basin projects in general, the meander characteristics must be quantified. Most of the studies have been concerned with the fully developed flow in a constant-radius; singular bend with uniform approach flow. A partial summary of these studies was given previously (Odgaard, 1981). The natural bend neither has a uniform approach flow; nor has a constant radius of curvature. The flow, generally, is in a state of either development or decay, or both. The purpose is to present an analytical approach to describe the flow and bed topography in such a channel (Odgaard, 1986). A change in channel curvature is as important as the curvature itself to the behavior of the bed profile. The model predicts that the secondary-flow component and the transverse bed slope react to the curvature changes like a damped oscillating system subjected to a driving force. The driving force can be any conceivable input function (an abrupt change in curvature, a harmonically oscillating curvature, or any other curvature variation).

Several formulas are theoretically and empirically proposed for the alternate bar wavelength (Ikeda, 1984). Due to dense population, most Japanese rivers are channelized, and many meandering rivers have been straightened. The emergence of alternate bars in these rivers destabilizes the channels, and induces subsequent side bank erosion.

Kinoshita (1987) found that the alternate bars are formed even in a straight laboratory flume with fixed side walls, and his subsequent field work revealed that the formation of alternate bars in straight rivers results in the development of meandering. Hayashi (1970) analyzed the flow in straight flumes with alternate bars with a potential flow model, and examined the stability of alternate bars. Hayashi and Ozaki (1980) treated the conditions of alternate-bar occurrence, and obtained the bar wavelength. Sukegawa (1971, 1972), Ikeda (1973), Kuroki et. al. (1975), Tamai et. al. (1978), and Muramoto and Fujita (1978) investigated the conditions of bar occurrence and proposed various empirical stability diagrams. Among others, Hansen (1967); Callander (1969); Engelund and Skovgaard (1973); Parker (1976); Parker and Anderson (1975); and Fredsoe (1978) presented theoretical studies on alternate bars. Field surveys are also documented abundantly, and much useful information is presented.

The objective of this paper is to describe qualitatively experimental and theoretical observations of meander evolution. Using dimensional analysis, Van Rijn (1984) concluded that H/λ, should be dependent on D^* (dimensionless particle parameter that reflects the effect of viscosity), T (= τ_*'/τ_{*cr}-1) and ds/h.For most of the data, no appreciable influence of D^* on the steepness was detected. Several rules may be stated from the observation of Yalin's (1977) arguments: Ripples may only occur at the lowest sediment transport rates close to the initiation of grain motion, since those transport rates of grain sizes for which ripples are possible (ds<0.7 mm) (Raudkivi, 1976) are inevitably associated with small Re^*. For a given grain size, a sediment transport rate exists for which dunes with superimposed ripples begin to form. As the transport rate increases above this value, so does the size of dunes, while the ripples steepness decrease and finally comes to zero. At this range of dual bedforms, H/λ, ought to be a certain combination of both form dimensions.

1.1 Investigation of bed formations at the meandering channels

In order to investigate the reason of bed formations at the meandering channel theoretically, the knowledge of the oscillatory flow field near a wavy sandy bottom is needed. To that end, in a meandering stream model of a wavy sandy bottom, experimental observations of meander evolution are described qualitatively. The second part of experimental procedure consists of a description of the shear stress distribution changes of a straight channel with artificially wavy bottom during the meander development.

The form of the steady streamings set up in addition to the oscillatory motion by the bed profile is analyzed for different values of the parameters (Vittori, 1989). The non-linear viscous oscillatory flow over a wavy wall of small amplitudes is determined. The solution holds for arbitrary values of a^*/L^* (a^* is the amplitude of fluid oscillations near the wall and L^* is the wavelength of wall perturbation); previous work by Lyne (1971) and Kaneko and Honji (1979) are thus extended. An independent analysis for small values of a^*/L^* is performed by Vittori (1989), and the relevance of the results to the study of ripples formation at the bottom of sea waves is discussed.

In recent years many investigations have been devoted to the study of viscous oscillatory flow over a wavy wall in the study of the interaction between the meandering flow and meandering channel boundary layer in the nearbank region. Indeed it is well-known (Sleath, 1984) that a slight sinusoidal perturbation of the bottom in an oscillatory flow modifies the flow field so that steady streamings of the type described by Stuart (1966) can be observed. These steady drifts consist of recirculating cells whose form, intensity and direction depend on the values assumed by relevant parameters (Vittori, 1989). As the sediment of the bed is driven by the stress field associated with the fluid motion, a steady drift directed from the troughs towards the crests of the perturbation, may lead to the growth of the latter and thus to a pattern of sand waves (rolling grain ripples). Once formed, ripples will not continue to grow indefinitely; the steady drift is modified by non-linear effects and as ripples get steeper an equilibrium configuration is reached for which the gravity force acting down the slope balances the stress field associated with the fluid motion. Moreover when the ratio between the height and length of the ripples exceeds a value ranging about 0.1 the flow separates behind the crests and leads to vortex shedding which modifies the flow field and the ripple pattern. The latter was named vortex ripples by Bagnold (1946), who first introduced a distinction between sea-bedforms for which flow separation is absent (rolling-grain-ripples) and those which cause flow separation (vortex ripples). Lyne (1971) studied the flow induced by fluid oscillations near a wavy wall of amplitude (a dimensional quantity) much smaller than the characteristic viscous length. However, Lyne (1971) restricted his attention to the cases of small or large values of the ratio between the amplitude a^* of fluid oscillations and the wall wavelength L^*. Furthermore, Kaneko (1981) proposed a numerical solution in the same range of values of the parameters and a^*/L^*. As pointed out by Sleath (1984), the limited applicability of the solutions for small and large values of a^*/L^* lies in the fact that ripples usually form for values of a^*/L^* of order one. According to Vittori (1989), a second harmonic with amplitude of second order is introduced in the bed profile to describe the flow over a rippled bed with sharp peaks and flat troughs.

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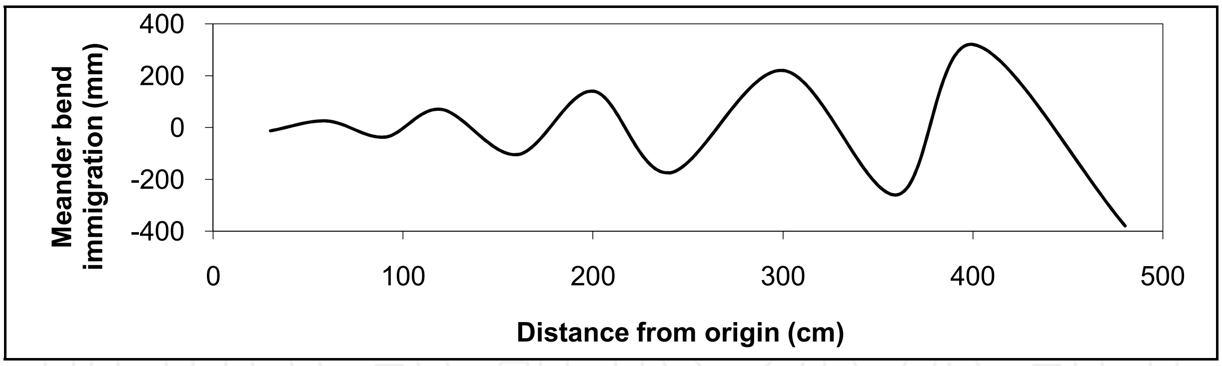
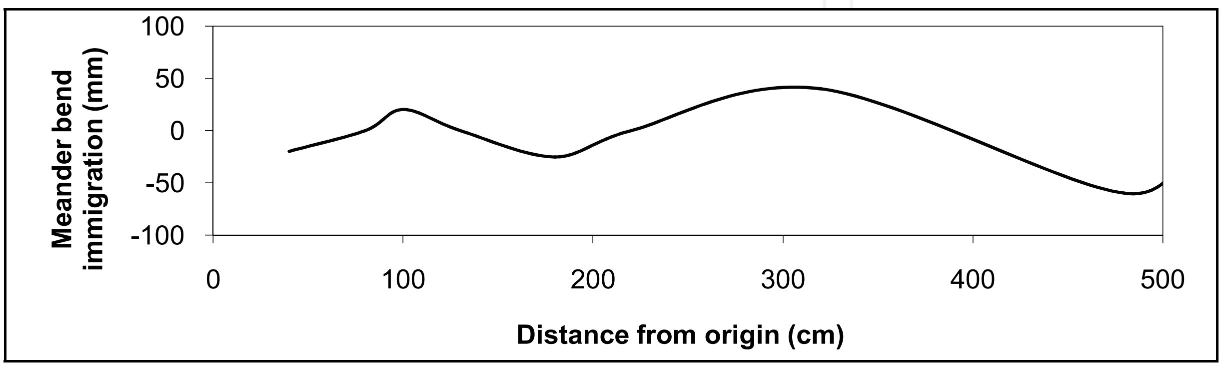


(a)



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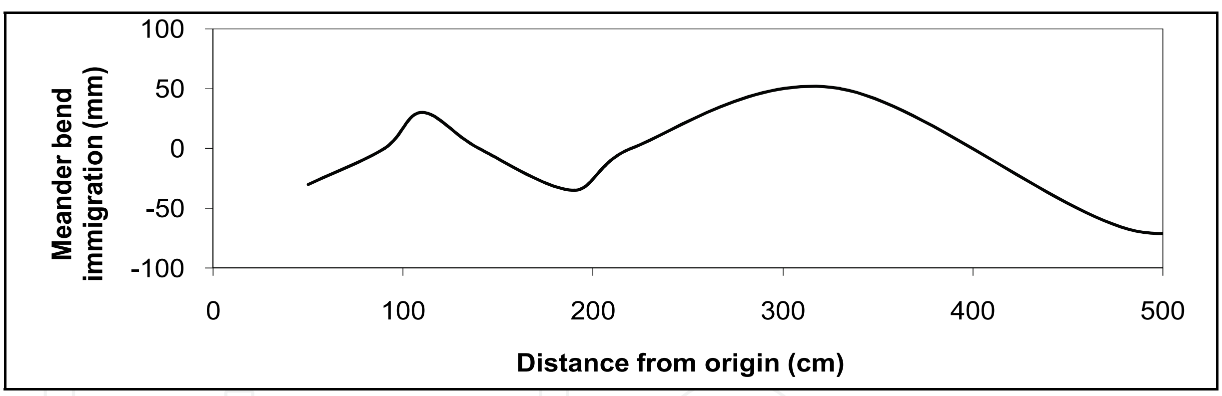

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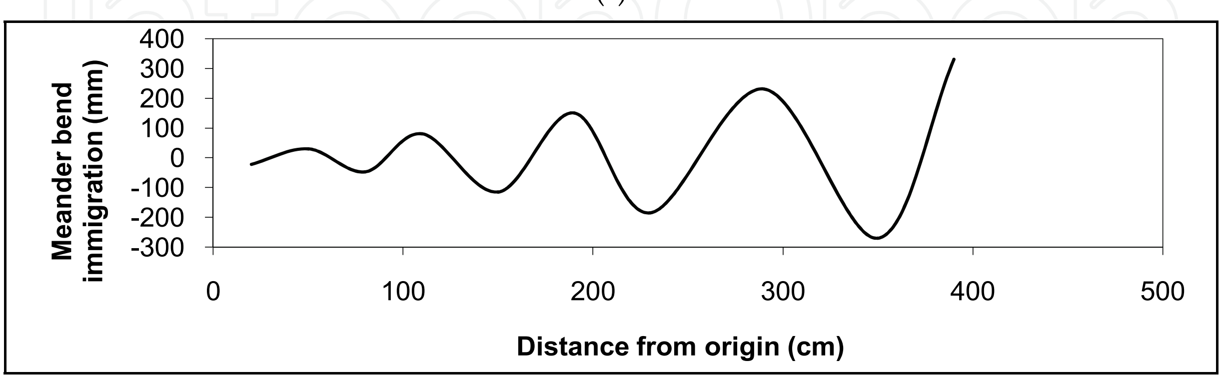

(d)

Fig. 1. Fully developed meandering channel patterns for various of discharge (Q) and bed slopes (So) of the channel after 72 hrs.

The bends of a meandering river have limited widths and lengths. The flow and the hydraulic properties of the meandering river, the amount of sand moving along the bed, and the rate of bank erosion determine these limits. When a bend reaches this width, a chute forms and a new bend develops farther downstream. Distorted bends and natural cut-offs are caused by local changes in the character of bank materials.

2. Experimental study

A movable laboratory channel with varying slope was installed for an experimental study of the meander evolution, for measuring the shear stress at the meandering channel, and for studying the sediment-water interaction at meandering channel. The main channel, as shown in Figure 1, was 10.00 meter long, 1.60 meter wide and 0.42 meter deep. There was movable carriage on the side rails, 8.80 meter long, which was situated for measurement of laboratory stream characteristics. Water coming from the head tank passed through the water tranquilizer which was 1.60 meter wide and 0.26 meter long and 0.65 meter deep. On the bottom of the channel an artificially wavy bottom was put in the middle of the straight initial channel. While the water flow through the straight canal, experimental observations of discharge, slope of the main channel, and shear stress distribution on the wavy bottom were made. An analytical model of free-surface flow over an erodible bed is developed and used to investigate the stability of the fluid-bed interface on an artificial wavy bottom, which gives the same characteristics of the bed features by measuring the oscillatory shear stress distribution with the hot-film sensors on the artificially wavy bottom in a laboratory canal . The downstream reservoir for outflow with the end gate was 1.10 meter long, 1.60 meter wide and 0.65 meter deep.

It is often considered that an irregularity in the bankline or another causing factors will disturb the flow and cause meandering. In an effort to ascertain the fundamental causes of meandering, a test was conducted in which a constant rate of flow was passed through a straight channel with artificial wavy bottom and at the oscillatory boundary layer the shear stress distribution in form of shear velocity is given in Table 1. and Figure 1.

As a result the shear stress distribution at x-coordinate is given as

$$\tau_{ox} = \tau_o (1.0 - 0.5 \cos (kx - \sigma)$$

from the experimental investigation.

The movable carriage on the side rails was very helpful for setting the profile indicator instrument and the velocity measurement instrument for obtaining the geomorphological and physical characteristics of meandering channels. For every run, it was easy to change the slope, the discharge and other parameters using the laboratory channel with variable slope.

Other test was conducted in the initial straight channel, artificially carved in uniform sandy material, through which a constant rate of flow was passed which had a velocity of 20 cm/s and which was sufficient to move sand along the bed and to erode the banks (Figure 2). The sediment supplier for the feedback system lays at the entrance after the tranquilizer. The sand collector , 0.42 mx1.60mx0.65m, was at the end of the channel. The flume channel on the laboratory alluvial boundary layer was 8.80 meter long and had a trapezoidal cross section, which was carved in the uniform sand of 1.35 mm of median diameter, with a bottom width of 0.10 meter and water width of 0.20 meter and 0.10 meter depth. The end gate from the end water tank to the sediment collector part of the channel was 0.15 meter

x/L (Distance)	Elevation from bottom (mm)	Run.1 (τ_{max}= 100mN/m²)	Run.2 (τ_{max}= 239mN/m²)	Run.3 (τ_{max}= 300mN/m²)	Run.4 (τ_{max}= 390mN/m²)
0	-5.00	0.63	1.06	1.27	1.5
0.05	-4.00	0.64	1.17	1.32	1.58
0.1	-3.00	0.655	1.30	1.40	1.77
0.15	-2.00	0.84	1.40	1.50	1.89
0.20	-1.00	0.92	1.5	1.67	1.96
0.25	0.00	0.97	1.58	1.78	2.06
0.30	1.00	1.09	1.70	1.93	2.2
0.35	2.00	1.19	1.80	2.00	2.3
0.40	3.00	1.25	1.85	2.08	2.3
0.45	4.00	1.25	1.92	2.1	2.4
0.50	5.00	1.27	1.94	2.1	2.4
0.55	4.00	1.27	1.95	2.1	2.4
0.60	3.00	1.14	1.87	2.0	2.4
0.65	2.00	1.00	1.76	2.0	2.36
0.70	1.00	0.79	1.67	1.97	2.29
0.75	0.00	0.71	1.50	1.87	2.2
0.80	-1.00	1.0	1.58	1.80	2.1
0.85	-2.00	1.0	1.40	1.58	1.9
0.90	-3.00	0.72	1.25	1.48	1.7
0.95	-4.00	0.62	1.10	1.20	1.5
1.00	-5.00	0.556	1.10	1.19	1.4

Table 1. Shear velocity distribotion on the artifically wavy boundary layer (x/L versus u_*) (Re= 15 000 and v_{mean}=0.80 m/s)

wide and 0.15 meter high. No sand was fed at the entrance of the stream. Beginning with these initial conditions, the photographs show that the stream developed naturally. An initial straight channel was formed into the meandering channel on the uniform sand bottom of the main channel. The modification of the initial straight channel into the meandering channel took place after 320 hours of the flowing of the sand-water mixture at the initial straight channel. This time was very long for experimentation. After every experimental run, it was difficult to carve the initial straight channel on the meandering deformations and to change the initial hydraulic parameters. An equilibrium condition was reached after 32 hours from the beginning of measurements at the laboratory meandering channel. Like an original prototype, the feed-back system of sand took place at the entrance of the sand reservoir of the main channel. With a developing meandering channel, bed profiles and velocities were obtained by laboratory profile indicator instruments and velocity-measurement instruments. However, only secondary velocities were obtained. The characteristic along the shifting sinuous channel of a meandering river (Figure 2.b and c) which is result of the oscillatory boundary layer. The indentations along the boundaries of the meander belt are the banklines of earlier courses. Throughout the duration of the test the stream constantly shifted its path of flow in the mid and lower sections. It is noted in the photographs that the degree of meandering increased downstream.

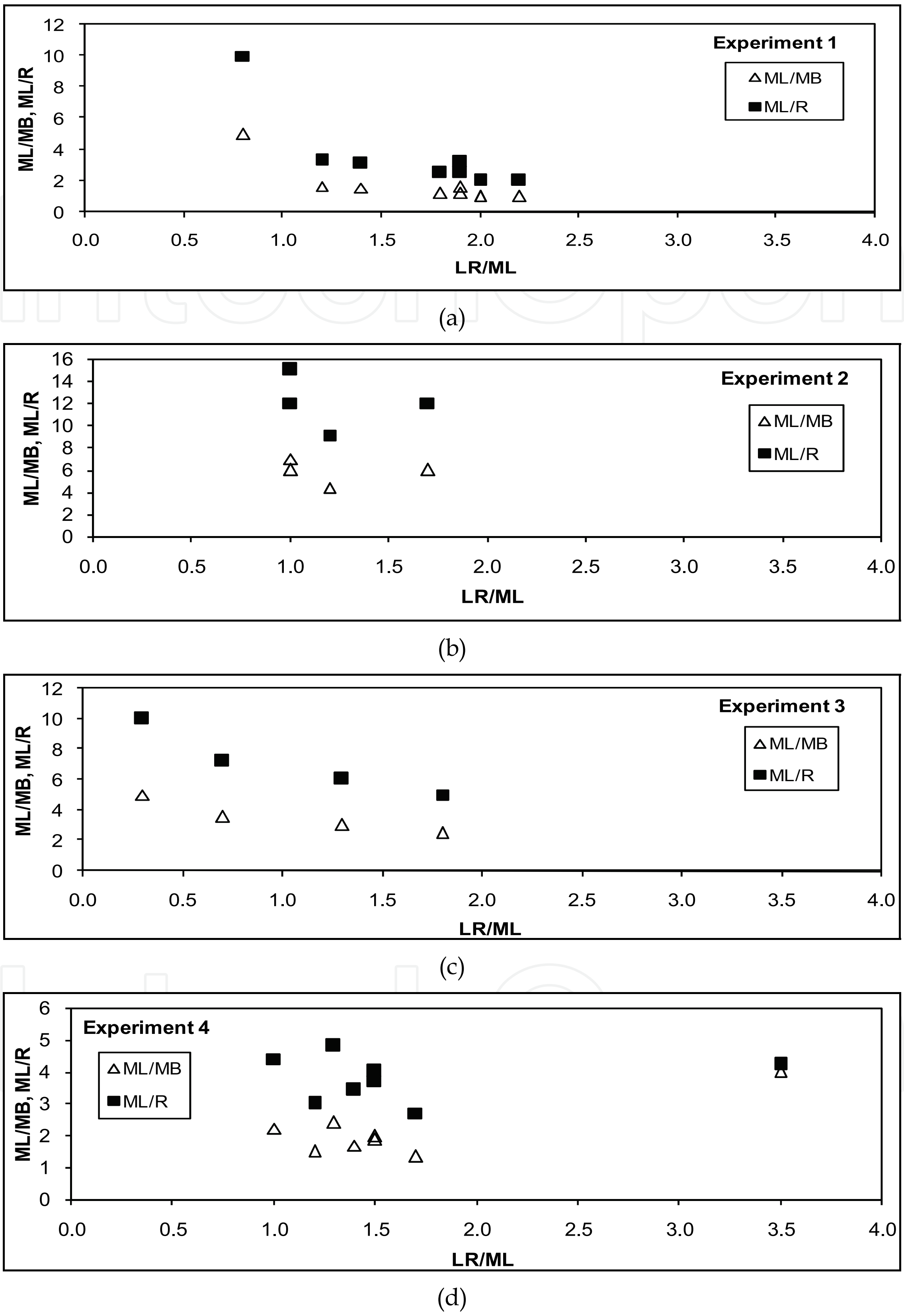

Fig. 2. Relation between tortuosity ratio (ML/LR) and aspect ratios of tortuosity, ML/MB and ML/R. ML = meander wave length, LR = meander bend length, R = meander bend, and MB = meander bend migration.

It was observed in the laboratory that the slope of the channel increased as it developed from the straight from through a shoaled condition to the meandering pattern, and that these three-dimensional channel forms were associated with significantly higher sediment transport rates than was the straight form. Due to the increasing gradient, the experimental channel would overflow its banks at the head of the system unless steps were taken to build up the banks to maintain a constant small freeboard. This was the standard procedure employed in the experimental program.

The laboratory observations provided a firm evidence of the association between the cause of meandering and an instability of sediment transport that was evidenced by the appearance of alternate shoals. Whether that instability aroses due to fluid or was caused by the bed sediment transport was not established by observations. Nevertheless, it was clear that the spacing of shoals was closely related to the wavelength of the meanders. It then follows that the spatial instability that generates alternate shoals also determines the wavelength of meanders. If an aggrading channel is permitted to overflow its banks, braiding occurs. Such a circumstance corresponds to a valley slope which is insufficient for the development of the hydraulic gradient necessary to transport the discharge of sediment and water.As the channel attempts to steepen its gradient, aggradation through sediment deposition results in a braided system (Dietrich, et al., 1979).

The experimental set-up seems to be a good model of the prototype of a meandering river. It reflects the development of a meandering channel on the cohesionless bottom boundary layer, exhibiting every phase from the beginning to the end of the erosion event at the bank and the bottom boundary layer. To determine the average sediment transport rate in weight per unit time took much time after every experimental run, because amount of sand was taken from the sand collector for it and one had to wait for it to dry in otoklav (drying oven). To estimate every measured value at the sand transport curve took too much time.

The experimental model in the present study consists of a very simple straight channel, which showed, after some time, meander planforms on the sandy bottom of the main channel. It was difficult to take some measurements at the meander bends. The sediment-transport rate took place before the meandering planform occurred. From experimental observations, it was seen that there was no sediment transport after meandering and the stability of the flume was observed with the meandering planform. One of the limitations of the experimental set-up was not observing the braiding planforms.

The measurement of sediment transport by weighting the dry sand amount at the end of the flume was error prone. In the prototype there is no influence of the dried sand transportation in the river erosion. The experimental procedure is used to find a relationship between the sediment transport in laboratory flume and that in the main channel. The sand transport distribution for every short time duration was not measured, although sediment transport equations may need a detailed sand transportation curve. Also, flume erodibility is not the only limiting factor for cross-section widening. When a cross-section becomes very wide and shallow, its cross-sectional shape may become unstable and develop into a number of separate, narrower channels, thus transforming into a braided or an anabranching river. In the experimental procedure, limited runs were taken, only for achieving the meandering planforms, but for braided or anabranching river cross-sections, the experiment was not continued. The main channel slopes varied between 0.04% - 0.5%. The main channel discharge varied between 0.07 l/s –0.73 l/s.Outside of this range, measurements could not be made for experimental limitations. The transported bed material weight in time was given for Q = 0.1536 l/s and J=0.08%. These values were restricted one for the given bed-load equation and for the meander-bend equation because of laboratory measurements difficulties. Out of this range of the main canal slope, the flow in the flume of sandy bottom varied from subcritical form into the supercritical form. That is why, one must provide more universal equations for bed load transport and for meandering bend planform equations.

3. Analysis of data and discussion of results

Following the preliminary experimental results, experiments with proper discharge and slope combinations were planned. Also, additional experiments were arranged to check the repeatability of the meander tests and to examine the meander performance at the extremes of steep and flat slopes. For each test, the flow had to be prepared at the beginning. This was done according to the following procedures. (1) The bed material throughout the whole flume was loosened. It was necessary because otherwise the sand could be cohesive and resistant to erosion. (2) The initial straight channel and the flood plain were formed. This was done by moving the carriage along the flume. On the carriage, a blade was fixed, which scraped the sediment to form a smooth flood plain. Meanwhile, a properly designed template was fixed on the blade cut into the sediment bed to form the initial channel along the center line of the flume. The cross-section shape and area of the initial channel along the center line of the flume were decided by the geometry of the template. The initial channel and the flood plain created in this way assumed the same slope, declining in the downstream direction. (3) The sediment was compacted. A certain compactness of the sediment bed was necessary in order to prevent the sediment from being easily washed away just as the flow entered the flume. (4) Both end-boundaries of the channel were shaped. At both upstream and downstream ends, the initial channel boundaries had to be carefully prepared in order to provide gradually changing sections for the entrance and exit of water flow.

The experimental results are presented in two parts. The first part consists of a description of what the shear stress distribution changes during the meander development. In the second part, experimental observations of meander evolution are described qualitatively. Generally, in the laboratory channel two different types of the meander development were observed, with and without sediment feeding at the entrance of the channel. At the beginning of the test when the flow front just reached the downstream end of the initial channel, sediment transportation took place immediately in terms of bed load. The initial flow velocity was about 40 cm/s. The eroded sediment was mostly from channel banks rather than from the bed. About 25 minutes later, the channel width increased from the initial width 10 cm, to 24 cm; the channel still remained straight. After another 10 minutes ripples (length = 40 cm) could just be seen on the channel bed, and they were moving in the flow direction with a speed of about 16 cm/s. Meanwhile, the ripple length became longer and longer and tended to be alternate bars. When elapsed time was about 30 minutes the ripples developed into alternate bars with an average bar length, approximately equal to 90 cm. Starting from that moment, the bed topography was dominated by the regular alternate bars, which seemed to begin to exert some influence over the main flow. The flow direction was changed from its initial course and diverted according to the shape of the bar

boundaries. Intensive bank erosion began to occur at the places where the flow tended to join the bank, and deposition occurred where water flowed away from the bank.
Although the main course of the channel was still essentially straight, a sinuous thalweg was noticeable. As the erosion at one bank and deposition at another continued a meandering channel was created, with a regular zigzag form. Later, a meander channel became noticeable, the meander bends started to expand in a transverse direction. Meanwhile the bend apexes started to move in the downstream direction. The lateral bend movement, known as bend expansion, initially progressed at a speed higher than that of the bend’s movement in the down-valley direction which is known as the bend migration (Figure 2 b and c). However, after about one hour, the bend expansion stopped, while the bend migration not only continued but showed no sign of a decrease in speed. At this stage, despite the bend migration, the meander bends assumed substantially the same size and pattern. Hence, the meander plan form geometry became more or less constant. This condition of a meandering river is defined as the stabilized meander.

3.1 Analysis of data in the shear stress distribution on the wavy bed

In this part of experimental procedure, a given discharge was allowed to flow in the flume with a wavy bed. The uniformity of flow was ensured by adjusting the depth of flow constant near the entrance and exit reaches of the flume. The oscillating shear stress distribution on the wavy bed of the channel was measured with a hot-film-WTG-50-sensor. A technique developed by Gust (1988) measured skin friction in flume boundary layers, with and without suspended particulate matter, by constant temperature anemometry. The experimental setup consisted of a 1.5 m wide and 1.5 m deep rectangular flume (10 m). The straight length of channel had a bottom covered with artificial waves of iron plate, as the same of the walls with wave length of 120 cm, and amplitude a=2 cm. The clear water supply was obtained from a 5 m high overhead tank. In order to study the effect of oscillating shear stress distribution the bottom slope was changed. In the second part of experiments, skin friction measurements were made with an array of flush-mounted-hot-films at 24 points on the different slopes of one of a field of two-dimensional immobile artifically made dunes in the straight channel. The total boundary shear stress was also measured.
With sensor scales of 3 mm and frequency responses of 20 Hz flush-mounted, epoxy-coated hot films yielded mean and fluctuating components of wall shearing stress at different water depths. Fluctuating components of the skin friction are present in all turbulent flows, including those of hydrodynamically smooth walls (Eckelmann, 1974), and require consideration in turbulent flow of calibration techniques. In experimental runs mean friction velocities are obtained by multiplying recorded mean voltage signals by calibration coefficients obtained through either polynomial or exponential least squares fits of the calibration data. In turbulent flow the calibration curve of instantaneous (equal to mean) skin friction can be expressed for constant temperature anemometry as

$$\tau^{1/2} = A_t E^2 + B_t \qquad (1)$$

where the coefficients A, B are determined by a least squares fit from the shape of the calibration curve (Hanratty and Campbell (1983)).

4. Comparison with previous studies

Paola (1983) used similar hot film anemometry technique to measure skin friction and close-to-bed velocity profiles over fixed ripples of median grain size of 0.2 mm in a flume experiment. The ripples were 1 cm high and 10 cm long. His results thus should be comparable to those of the present study. His measurements were obtained under a range of roughness Reynolds number $Re_*=Hu_*/\nu$. He obtained the total shear velocity u_* from the energy gradient method. Estimates of this shear velocity from available velocity profiles agreed well with the values from the energy gradient method. Skin friction shear velocity u_{*s} was measured at four locations on the stoss slope of a ripple and were then spatially averaged. The data points closely follow the diagonal line, suggesting a good agreement between the measured shear velocity and those predicted by the model. Data from Paola (1983) and Zilker et al. (1977) show that u_{*s} obtained from the inner boundary layer velocity profiles relatively far above the sand bed decreases from the ripple trough to the crest. This trend is just opposite to the u_{*s} measured using the skin friction probes, though the spatially averaged values of the two methods do not differ significantly. A recent study by Nelson and Smith (1989) also shows that logarithmic fit to the whole inner boundary layer velocity profile will underpredict u_{*s}. Based on these findings, the inner boundary layer ripple crest velocity profiles of Paola (1983) have been fitted to the van Karman-Prandtl equation to obtain the profile-based skin friction shear velocity. The results of the present study and data from previous investigations generally support the application of the shear stress model to sand ripples for partitioning skin friction and form drag from known grain size, ripple geometry and conventional outer boundary layer velocity profiles. Though the model is relatively simple, it does require iterative calculations, and uncertainties exist in various coefficients. It is preferable, therefore, to derive some overall empirical relationships between outer boundary layer shear velocity u_* and inner boundary layer skin friction shear velocity u_{*s}. This empirical relationship should provide approximate but easily derived estimates of skin friction over sand dunes from known dune geometry and the outer boundary layer shear velocity..

The ratio of the inner boundary layer shear velocity u_{*s} and the outer boundary layer shear velocity u_* in a unidirectional flow is mainly controlled by the flow condition, grain size and dune geometry. The flow condition is represented by the total shear velocity u_* and the dune character can be represented by the dune height H since the aspect ratio H/L is roughly constant for natural current dunes (=0.05). Therefore, a universal empirical relationship between the ratio u_{*s}/u_* and a flow dune parameter u_*/H can be used to properly estimate u_{*s} from u_* and H. Due to acceleration and deceleration of near-bed flows over bed forms, flows tend to separate at the dune crest and a wake forms at the lee side of the dune (Raudkivi, 1967) . Higher ripple steepness and low to medium flow stresses have been found to favor this flow separation and wake development (Davies, 1980; Smith, 1977). At low u_*/H ratios (2.3), the smaller flow stress and or bigger ripple height determine that the flow is separated and lee side wakes are fully developed. Under this condition, u_{*s} increases relatively faster than the form drag as flow becomes stronger. Thus, u_{*s}/u_* increases systematically with u_*/H. When the flow dune parameter u_*/H is beyond the critical value of 4.2, the flow stress becomes very strong and sand bypassing occurs. Under this condition, the dune height is reduced and wakes start to break down, and flow is no longer fully separated. These will cause a dramatic increase of drag and hence increase of total shear velocity u_*.

5. Conclusions

The flow resistance in a meander bend is considerably increased due to the form resistance of the patterns about which much is not known. It depends on a number of factors including grain friction, form resistance of two- and three dimensional patterns, skin friction of the non-separated oscillatory component and the sediment transport rate. The following results from the investigation were obtained:

The measured skin-friction field is consistent with a simple model for sediment transport over bed forms, where the fluctuating skin friction is important. The data are also consistent with the drag-partition theories of Engelund (1966) and Paola(1983). Normalized skin-friction spectra vary with stream-wise position but not vary with Reynolds number.

6. Definition of terms

The tortuosity ratio determines the shape of meanders. For any one value of tortuosity ratio, there are associated single values of the ratios of:

1. Length along river bend to radius of center line of bend: (LR/R)
2. Straight length along the river valley to radius of center line of bend: (ML/R);
3. Meander belt to radius of center line of bend (MB/R);
4. Angle of bend to radius of curvature (θ/R).
5. Meander length to meander belt (ML/MB)

7. Analysis

As shown in Table 1, four experiments were conducted with discharge varying from 0.08 to 0.50 l/s and slope changing from 0.08 to 0.35%. In this table, F_o is the Froude number, which was determined using the velocity and depth measured at the extreme upstream end of the channel. In Table 1, R_e is the Reynold's number that is computed taking kinematic viscosity equal to 1.57×10^{-5} m^2/s, which corresponds to the standard temperature and pressure (STP). MBN represents the number of meander bends occurred in the initially straight channel after 72 hrs of the experimentation. L, LR, and MB represent, respectively, the straight channel length, total meander bend length of the channel, and the maximum migration of the initially straight channel. Some of these terms are defined in Fig. 1. In this figure, θ is the central angle of the meander bend and R is the radius of the bend. The resulting forms of the meandered channel in the four experiments are shown in Figs. 2a-d, which correspond to experiments no. 1 through 4, respectively.

It is apparent from Table 1 that the number of meander bends (MBN) increases with the increase in either F_o or R_e and vice versa. It implies that the number of meandering bends depends on the flow regime described by the Froude and Reynold's numbers. The ratio of the total length of the initially straight channel, L, to the total meander length of the channel, LR, describes the tortuosity of the meandering channel. It is an indicator of the meander formation; if L/LR is equal to 1, the channel does not meander at all and if LR approaches infinity, the tortuosity ratio approaches zero, implying that the tendency of a channel to meander increases with the reduction in the tortuosity ratio and vice versa. It is seen from table 1 that the tortuosity ratio decreases with the increase in either F_o or R_e and vice versa. It leads to inferring that the flow in the regime of low velocity and high depths allows an alluvial channel to meander less than in the otherwise situation.

The above results, however, deviate much from those observed in the field and shown in Table 2 for some rivers. The ratio L/LR for laboratory channel (Table 1) varies from 0.033 to 0.048 whereas it ranges from 0.035 to 0.582 in natural rivers, implying that the natural rivers will meander less than the laboratory channels even though both are in the same flow regime. It leads to inferring the prominent role of boundary conditions in meandering. Laboratory channels are usually of restricted geometry (length and width) whereas the natural rivers may adopt any size. The channel characteristics are connected with meander geometry. For example, wide shallow channels exhibit lesser tortuosity than narrow deep channels do and vice versa. Furthermore, the flow lines in the laboratory channel follow sharper curvature than in the prototype, indicating that deeper and narrower channels produce more acute bends (Rozovasky and Makkavuev, 1964). According to Rozovasky and Makkavuev (1964), the velocity of flow in transverse direction that causes river meandering is directly proportional to the depth and mean velocity of flow and inversely proportional to the radius of curvature. It is noted that the depth and the velocity of flow governs the regime of flow described by F_o and R_e. Thus, the inference of the results from laboratory channel is consistent with the results of earlier studies.

The above results, however, provide only an overall view of the meandering of the laboratory channel. A discussion of the individual meander forms of all the four experiments shown in Fig. 2 and summarized in Table 3 follows. In this table, the location describes the location of MBN and other columns describe its corresponding ML, MB, R, and LR. It is seen from the table that, in all the four experiments, the meander length (ML) and the radius of curvature (R) increase with the distance. It implies that the wave length (ML) increases in the direction of flow and vice versa. Since R also increases with ML, the increase in ML is coupled with the increase in the meander bend migration (MB), as also seen in Fig. 2. Thus, the meandering behavior of the laboratory channel expands in the direction of flow. Here, it is appropriate to mention a little about the role of the initial flow conditions that may be of significance in the process of meander development. For example, a meandering natural river at a certain location exhibiting certain meandering characteristics in a particular flow regime will differ significantly from the behavior of the laboratory channel in the same flow regime. It is because of the difference in initial and boundary conditions, which affect significantly the flow wave behavior in open channels (Mishra and Singh, 1999). Since the ratio L/LR describes local features of channel meandering, this ratio is sensitive to the considered river reach and, therefore, is larger in natural rivers than in laboratory channels.

The aspect ratio defined by ratio of the length along river bend to meander length (= LR/ML) in experiment 1 varies from 0.8 to 2.0, with most of the values near 2.0. In experiment 2, the aspect ratio varies from 1.0 to 1.7, with most values near 1.0; it ranges between 0.3 and 1.8 in experiment 3, and between 1.0 and 3.5 in experiment 4. The overall average of these values is of the order of 1.5.

The experimental meandering channel developments show the relationships between tortuosity ratio; LR/LV; and ML/R and ML/MB. Similar curves could be drawn for the other ratios. Important channel characteristics are connected with meander geometry. Wide, shallow channels are usually associated with lesser tortuosity. When distortion is used in hydraulic models, flow lines are found to follow sharper curvature than in the prototype, indicating that deeper and narrower channels produce more acute bends.

MB No:	ML (cm)	MB (cm)	R (cm)	*ML/MB	*ML/R	LR (cm)	LV (cm)	*LR/ML
Experiment no. 1								
1	50	10	5	5.00	10.0	40	50	0.8
2	25	20	10	1.25	2.5	45	25	1.8
3	25	25	13	1.00	2.0	50	25	2.0
4	50	30	15	1.67	3.3	60	50	1.2
5	35	35	18	1.00	2.0	70	35	2.0
6	50	40	20	1.25	2.5	95	50	1.9
7	70	45	23	1.56	3.1	100	70	1.4
8	50	50	25	1.00	2.0	110	50	2.2
9	80	50	25	1.60	3.2	150	80	1.9
Experiment no. 2								
1	45	8	4	6.00	12.0	75	45	1.7
2	105	15	8	7.00	15.0	100	105	1.0
3	150	25	13	6.00	12.0	150	150	1.0
4	165	38	18	4.40	9.1	200	165	1.2
Experiment no. 3								
1	50	20	10	2.50	5.0	90	50	1.8
2	75	25	13	3.00	6.0	100	75	1.3
3	175	35	18	5.0	10.0	50	175	0.3
4	180	50	25	3.60	7.2	125	180	0.7
Experiment no. 4								
1	10	3	2	4.00	4.2	35	10	3.5
2	30	20	10	1.50	3.0	35	30	1.2
3	30	13	6	2.40	4.8	40	30	1.3
4	50	23	11	2.22	4.4	50	50	1.0
5	40	20	10	2.00	4.0	60	40	1.5
6	55	33	16	1.69	3.4	75	55	1.4
7	65	35	18	1.86	3.7	95	65	1.5
8	60	45	23	1.33	2.7	100	60	1.7

Note: ML = meander wave length, MB = meander bend migration, R = radius of meander bend, LV = thalweg, superscript '*' indicates measures of tortuosity of the channel.

Table 3. Detailed features of the meanders in four experiments

From Table 1 the longest meander bend length in thalweg is given in the smallest discharge and bed slope as in the experimental run number 1; Q= 0.08 l/s; and S_o=0.08%. The meander bend number was in 500 cm length from the origin to the experimental measurements are 9. Tortuosity number = Meander wave length/ Meander bend length was (ML/LR = 475/15100 = 0.03146) the smallest, but meander bend migration after 72 hours was 50 cm, the largest, because of the smallest bed slopes (S_o= 0.08%).

The second longest meander bend length in thalweg is given in the experimental run number 4, which has the discharge Q=0.50 l/s; S_o= 0.35%. The meander bend number was in 400 cm distance in the observations from the origin was 8. The tortuosity number has the second biggest value as: ML/LR=400/11900= 0.0336, but the meander bend migration after 72 hours was 45 cm, as the second largest migration.

The third biggest tortuosity number (ML/LR=500/11300= 0.044) belongs to the third experimental run, with Q= 0.40 l/s, and S_o= 0.20 %, which has altogether 4 meander bend numbers.

From the figure of fully developed meandering channel patterns for various discharges (Q) and bed slopes (S_o) of the channel after 72 hours are given below results:

a. Figure (a) and (d) show similar trends, and (b) and (c) have no much meander bends.
b. After 72 hours of the experimental run the boundary layer material is compacted and does not show many changes in small bed slopes like at the experimental run (a). If we change the slope from S_o= 0.10%, and S_o= 0.20% to S_o= 0.35% and the discharges from Q=0.08 l/s, and Q= 0.20 l/s, and Q= 0.40 l./s to Q=0.50 l/s, and S_o= 0.35% it is observed the planform changes like at the beginning of the experiments, because the compactness of the sand material is too much after 72 hours.

From the Table 1, meander bend migration after 72 hours is only 50 cm like in the first experimental run, but the smaller meander bend number as 4 is the same with the experimental run in number 2 with Q= 0.20 l/s, and S_o= 0.10 %, but the tortuosity number is with ML/LR= 500/10500= 0.0476 is the biggest one, because second experimental run has the shortest meander bend length in thalweg like totally 10500 cm. It means if the meander bend length in thalweg (LR) is shorter, it has the biggest tortuosity number as ML/LR=500/10500=0.0476.

From the Table 2, giving the details of all features of meanders, the biggest ratios of ML/MB and ML/R for tortuosity grade, the second experimental run shows with Q= 0.20 l/s, and slope as S_o= 0.10%, ML/MB= 6 and ML/R=12, which has the meander bend number as 4. The second largest values (ML/MB=5) and ML/R=10 value is given in the experiment number 1, by Q=0.08 l/s; and S_o= 0.08 %, which has meander bend number as 9. These comparisons show that there is no necessity for having the largest meander bend number for large tortuosity ratios.

The third tortuosity ratio belongs to the experimental run number: 4, with Q=0.50 l/s; with slope S_o= 0.35%, which has the tortuosity ratio ML/MB=4 and ML/R= 4.166 at the first meander bend. The last values at the fourth experimental run with bend number as 8, which has ML/MB=1.33 ratio and ML/R=2.66 are the smallest in comparing with the other experimental runs. The first experimental run has the biggest meander wave number as 9, number 2 has 4 and number 3 has also 4, but the last run has also 8 meander bends. It means, if the boundary layer material is compacted after the 72 hours, it has the biggest discharge as Q=0.50 l/s, and the biggest slopes as S_o= 0.35%. It means for more tortuosity ratios we need the biggest discharge and the biggest bed slope in laboratory conditions.

Comparison of the laboratory meander tortuosity with the natural river meander tortuosity: Data is taken from Langbein and Leopold (1966) for the natural river meander tortuosity and gives the below results: The prototype for the laboratory meanders is choosen as San Juan River, Utah, and has this values:

ML (miles)	MB (miles)	R (miles)
1.2	2.4	2.0
1.8	2.7	2.3
2.2	2.9	2.5

The tortuosity ratio is ML/MB = 1.2/2.4 = 0.5 and the other ratio is ML/R = 1.2/2.0 = 0.6 Comparing these values with the laboratory values, the laboratory meanders are not well developed because of the canal bottom slope, but in natural meander bends, with the whole developed bends the tortuosity ratio is too small, when comparing with the laboratory data, ML/MB = 6 and ML/R = 5 and natural data gives 10 times smaller values.

Experiment No.	L (cm)	Discharge (l/s)	Slope (%)	F_o	$^*R_e$	MBN	LR (cm)	L/LR	MB (cm)
1	500	0.08	0.08	0.040	12658	9	15100	0.033	50
2	500	0.20	0.10	0.010	3165	4	10500	0.048	38
3	500	0.40	0.20	0.020	6329	4	11300	0.044	50
4	500	0.50	0.35	0.025	7911	8	11900	0.042	45

Note: F_o = Froude number, R_e = Reynold's number, MBN = number of peaks and troughs of the channel after meandering, L = straight channel length, LR = meander bend length, MB = largest meander bend migration, and L/LR = tortuosity number. *kinematic viscosity is taken equal to 0.157×10^{-6} m^2/s.

Table 1. Meandering characteristics of the laboratory channel

River	Location	Slope %	MBN	L (mile)	LR (mile)	L/LR	MB
San Juan	Utah	-	4	0.43	0.739	0.582	200 ft
Popo Agie	Wyoming	0.20	3	0.24	0.426	0.563	150 ft
Mississippi	Greenville	-	3	5.00	19.00	0.263	3.6
Potomac	West	-	3	6.63	14.25	0.465	1.5
Pole Creek	Wyoming	0.21	2	0.14	3.978	0.035	300 ft

Note: MB No. = number of peaks and troughs of the channel after meandering, L = straight channel length, LR = meander bend length, MB = largest meander bend migration, and L/LR = tortuosity number. *kinematic viscosity is taken equal to 0.157×10^{-6} m^2/s. '-' implies not available

Table. 2. Meandering characteristics of some natural meandering rivers

MB No:	ML (cm)	MB (cm)	R (cm)	*ML/MB	*ML/R	LR (cm)	LV (cm)	*LR/MB
Experiment no. 1								
1	50	10	5	5.00	10.0	40	50	0.8
2	25	20	10	1.25	2.5	45	25	1.8
3	25	25	13	1.00	2.0	50	25	2.0
4	50	30	15	1.67	3.3	60	50	1.2
5	35	35	18	1.00	2.0	70	35	2.0
6	50	40	20	1.25	2.5	95	50	1.9
7	70	45	23	1.56	3.1	100	70	1.4
8	50	50	25	1.00	2.0	110	50	2.2
9	80	50	25	1.60	3.2	150	80	1.9
Experiment no. 2								
1	45	8	4	6.00	12.0	75	45	1.7
2	105	15	8	7.00	15.0	100	105	1.0
3	150	25	13	6.00	12.0	150	150	1.0
4	165	38	18	4.40	9.1	200	165	1.2
Experiment no. 3								
1	50	20	10	2.50	5.0	90	50	1.8
2	75	25	13	3.00	6.0	100	75	1.3
3	175	35	18	5.0	10.0	50	175	0.3
4	180	50	25	3.60	7.2	125	180	0.7
Experiment no. 4								
1	10	3	2	4.00	4.2	35	10	3.5
2	30	20	10	1.50	3.0	35	30	1.2
3	30	13	6	2.40	4.8	40	30	1.3
4	50	23	11	2.22	4.4	50	50	1.0
5	40	20	10	2.00	4.0	60	40	1.5
6	55	33	16	1.69	3.4	75	55	1.4
7	65	35	18	1.86	3.7	95	65	1.5
8	60	45	23	1.33	2.7	100	60	1.7

Note: ML = meander wave length, MB = meander bend migration, R = radius of meander bend, LV = thalweg, superscript '*' indicates measures of tortuosity of the channel.

Table 3. Detailed features of the meanders in four experiments

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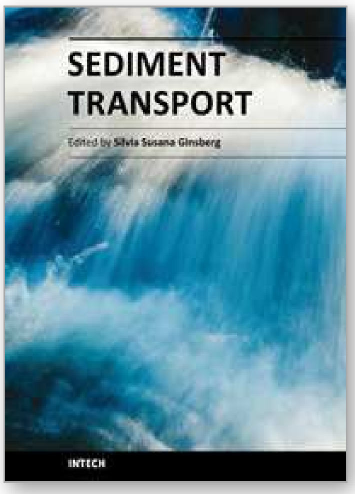

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Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.