INVESTIGATION OF THE MEANDER PLANFORM DEVELOPMENT IN A LABORATORY CHANNEL

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Abstract: Experiments were conducted in an initially straight laboratory alluvial channel to investigate channel meandering characteristics. The experimental observations revealed an empirical relation between three types of tortuosity ratios used for describing meandering characteristics. Furthermore, the Strauhal number was found to be higher for bed material with greater resistance to erosion than with lower resistance to erosion. The meandering characteristics were also investigated using the concept of buckling employed in solid mechanics and the concept of siphoning of fluid mechanics. The buckling of flow, attributable to the flow nonuniformity across the channel cross-section, was found to follow the same pattern as did meandering observed experimentally. The processes of expansion of meanders and cut-off can be explained using the concept of siphoning. The results of expanding meander planforms observed in four experimental tests supported the viability of these concepts.

1. INTRODUCTION

Laboratory flume studies and observations on alluvial channels suggest that the river channel planform is primarily governed by the flow discharge, sediment transport, channel slope, channel average roughness and the sediment composition of the channel boundary. The flow discharge and sediment transport represent the delivery of water and sediment from the upstream catchment area under the influence of climate, topography, geology and vegetation cover (Knighton, 1984). The supply and delivery of water and sediment are affected by a variety of influences within the catchment and river channel system, including the land use, flow regulation, water abstraction and channel modifications, all of which impact the river channel form (Downs, 1994). The complex interactions between river channel processes and form has been discussed by Ferguson (1986), Knighton (1987), Miller (1991), Rhoads (1991, 1992), Park (1995), Pizzuto (1992), Huang and Warner (1995), among others.

The characteristics of meandering planforms of alluvial rivers are important for planning, design, construction, or maintenance of bank-erosion control structures and river-basin projects in general. Such projects are needed to protect people who live along river banks due to the easy availability of water, fertility of land, productivity of food grains, and economic navigation and transportation of goods. To that end, it is necessary to understand the planform characteristics of alluvial rivers.

The meandering form of a river channel is a self-induced plan deformation which is periodic (ideally) and asymmetric with respect to an axis which may or may not be exactly straight. Accordingly, an alluvial stream, which deforms its initially straight channel into one of periodic and asymmetric plan form, 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 the stream itself, is not meandering (Chang, 1988). In practice, 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); the sinuosity generally varies in the range of 1.5 to 4.3 (Leopold et al., 1964). The valley slope provides the force which helps the channel straighten its course. The steeper the slope, the higher the mean velocity, requiring a flatter curvature for negotiating a curve. The relationship of channel slope to valley slope can be expressed by river channel slope = valley slope multiplied by the length along the valley / the length along the river.

The shape of meandering is influenced by the ratio of the length along a river bend (LR) to the length along a straight chord (LV), called tortuosity ratio which, in turn, can be expressed as (Chitale, 1966):

$$LR/LV = f(w, D, S, m)$$

where D = average depth of channel; S = slope of river; m = weighted mean diameter of bed sand. The ratio LR/LV determines the shape of meanders, and the meander size can be defined by the ratio of meander belt to channel width. 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 they do in the prototype, indicating that deeper and narrower channels produce more acute bends. Rozovasky and Makkavuev (1964) have shown that the component of velocity generating transverse flow in a bend is directly proportional to the depth and mean velocity in the vertical and inversely proportional to the radius of curvature. The effect of making a bend more acute would be the same as that achieved by increasing the depth of flow when the mean velocity of the channel is kept the same. Comparing two meandering streams carrying the same discharge and having the same mean velocity, the one having a deeper section should have more acute bends. Acute bends are associated with relatively fine bed material, whereas coarser bed material is associated with channels having low tortuosity. The non-periodicity of meanders which develop from a straight alignment in numerical simulations (Howard and Knutson, 1984; Crosato, 1990) suggest a dependence on initial and boundary conditions. Parker et al. (1982) indicated that skewing allowed equilibrium planforms in which the meanders had a finite amplitude and did not extend further.

Taking into account the nonequilibrium sediment transport, Nagata et al. (2000) developed a model for simulating the bed deformation and bankline shifting of an initially straight channel in a 2-dimensional planform. Using a stream classification system to describe the morphological stream types (Rosgen, 1994) and meander parameters were determined from empirical equations developed by Leopold and Wolman (1957, 1960). Hasfurther (1985), Brookes (1987), Newbury (1995) explained sinuosity in an empirical way. Gardiner (1991) and Boon et al. (1992) discussed asymmetrical cross-section, point bar development, two-stage channel design, floodplain approaches, pools and riffles recreation, and sinuosity. Modifications of the planform geometry can induce undesirable morphological and ecological consequences and significant channel adjustments that, depending on the energy of the flow, can result in failure of the restoration design through either erosion or sedimentation.

Mathematical models of meandering can be divided into kinematic models and dynamical models. In kinematic models, meander migration depends on geometrical properties of the river, notably a weighted average of local and upstream channel curvatures. In the dynamical models, meander migration depends on excess shear stresses or excess velocities of the near-bank flow, which are obtained from a linear computation of the flow field and the bed topography in the curved channel. The models of Ferguson (1983) and Howard and Knutson (1984) are kinematic and the models of Ikeda et al. (1981), Johannesson and Parker (1989) and Crosato (1990) are dynamical. Klaassen et al. (1993) followed a fluvial mechanism approach in their planform model relating to width adjustment, channel migration, island formation, channel creation and channel abandonment. Thorne et al. (1993) proposed that the general westward migration might also be explained as the development of a very large meander, which is plausible as a residual effect from all the westward and eastward migrations of the individual channels within the curved braid belt.

The objective of this paper is to qualitatively describe the evolution and development of meandering using the concepts of buckling of solid mechanics and siphoning of fluid mechanics. The viability of these concepts was tested using the data derived from the four sets of laboratory experiments.

2. CONCEPTS OF MECHANICS

2.1 Concept of Buckling

The concept of buckling is used in solid mechanics. In general, an eccentric loading of an elastic slender column leads to its buckling. The column buckles in the direction opposite to eccentricity. The shape of the buckled column depends on the amount of loading; eccentricity; and shape, size, and material of the column. In a given column, the shape of the buckled column primarily depends on the stress distribution within the column. The eccentricity-generated bending moment develops shear stresses in the column. These are maximum at the point of loading and minimum at the base of the column, leading to a skewed shape of the buckled column.

The above concept has been employed to describe the meandering (or buckling) flow paths of inviscid streams, straight jets in particular as shown in Fig. 1 (Bejan, 1994). The equilibrium centerline of the jet envelope is characterized by a sinusoid of infinitely small amplitude. The buckling wavelength λ_B is given as:

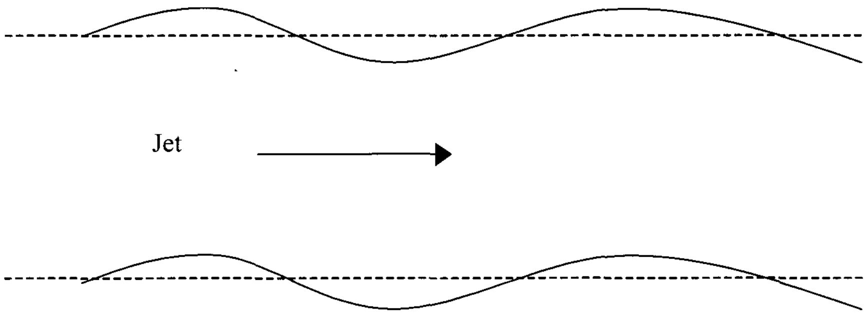

Fig. 1. Instability of a Sinusoidally Buckled Inviscid Stream.

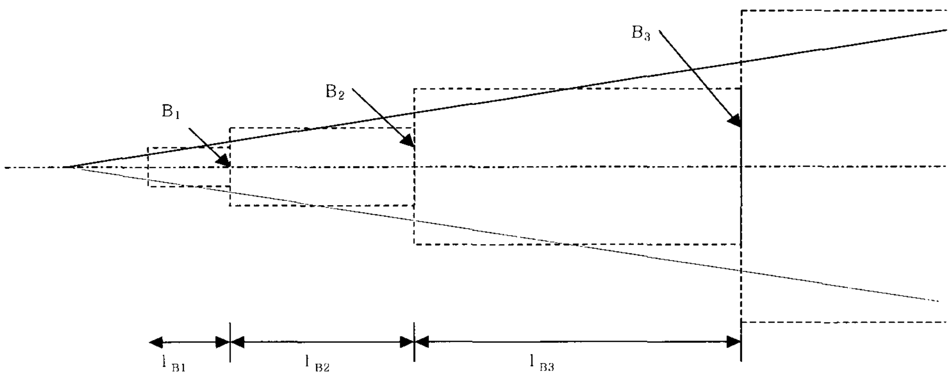

Fig. 2. Linear Axial Growth of the Time-averaged Stream Thickness in Jet Flow.

$$\lambda_B = 2\pi\sqrt{\frac{I}{A}} = 2\pi B \quad (1)$$

where I is the area moment of inertia of the jet cross-section, A is the area of cross-section, and $(I/A)^{1/2}$ is the transversal length scale, B. Fig. 2 describes λ_B and B in a linear axial growth of the time-averaged stream thickness in jet flow.

The natural frequency of jet fluctuation (Fig. 1) is expressed in dimensionless form as a Strauhal number (Bejan, 1994), S_t, a universal constant:

$$S_t = \frac{B}{\lambda_B} \quad (2)$$

The natural Strauhal number has a value of the order of 0.5. In this paper, the concept of buckling is utilized to describe the evolution of meanders. Their development is explained by the concept of siphoning.

2.2 Concept of Siphoning

According to the siphoning concept widely used in fluid mechanics, the flow from a higher elevation can be diverted to a lower elevation by first allowing the fluid to rise to a certain elevation. In a frictionless smooth pipe, the process of siphoning is driven by the difference of water elevation between the two (source and sink) water bodies and it continues till the continuum of flow is broken. Practically, the friction of the pipe primarily governs the extent of raising of the pipe. The siphoning will discontinue as soon as the pipe friction energy loss equals the driving energy of the elevation difference. This concept is used to describe the expansion of meanders downstream and the process of cut-off in alluvial streams.

3. DESCRIPTION OF MEANDERING PROCESS

3.1 Evolution of Meanders

To describe the process of meandering in an alluvial channel, consider a channel ACEG of Fig. 3, which was initially straight and, after a time, developed to follow the path ABCDEFG. As an elastic slender column buckles in the opposite direction of the eccentricity, the meandering process will evolve with the erosion of the left or the right bank of the channel, depending on the direction of eccentricity. If the initial velocity of flow at the entrance of the experimental channel (point A in Fig. 3) is not uniform across the channel cross-section, the resulting eccentricity in terms of momentum (or force) will initiate the process of channel erosion in the direction opposite to eccentricity, provided the velocity of flow is sufficient to counter the resistance of the bed material. For example, in Fig. 3, the right bank of the channel is eroded. It is noted that in an alluvial channel, the resistance to flow is governed by the level of compaction of the alluvial bed. It is known from the elementary soil mechanics that the compaction is a function of the moisture content and the silt/clay content of the soil. A moist sand will exert more resistance to erosion than a dry sand.

The meandering characteristics, such as wave length (ML), amplitude (MB), and radius of curvature, R, depend on the bankfull channel width (Leopold and Wolman, 1960), similar to the transversal length scale B in jet flow. Notations ML, MB, and R are described in Fig. 4. The radius of curvature of natural rivers is about 2.4 times the top width of the channel (Leopold and Wolman, 1960).

High flow velocities are likely to produce more acute bends than the flow of low velocities and vice versa. This phenomenon can also be explained by the shape of the buckled column, which will largely depend on the stress distribution along the column. For a given eccentricity, a heavier loading will lead to the more skewed shape of the buckled column than a lighter loading will do. Similarly, the planform of a meandering alluvial channel is likely to be more acute at the point of eccentricity than at some point downstream in a bend. It is noted that excessively acute meanders lead to flow separation (Chang, 1988) and, in turn, the discontinuity of flow.

3.2 Expansion of Meanders

Once the bank erosion due to buckling is initiated or induced, the channel will tend to erode its right bank up to the extent (point B in Fig. 3), the initial force (or energy) supplied at the entrance of the channel is balanced by the sum of the energy loss due to the boundary resistance and lateral slope. At this point, the net energy of flow will be equal to zero, the flow will be uniform, and boundary wall acting almost like a solid wall reflects the flow following the law of reflection, similar to light waves, so that the meander formation follows the path BC. This phenomenon is also valid for any point of time before the channel is fully developed. Due to the lateral slope of the bed and initial flow velocity at point B, the flow will be in the phase of acceleration, opposite to that in the flow path AB. The force of inertia will lead to eroding the channel in the same direction following B to C and continue to a point (earlier than point D) where the flow energy equals to the sum of the energy loss in the boundary resistance and lateral slope, if the longitudinal gradient is neglected. In meandering, natural or laboratory rivers expand in the direction of flow, as shown in Fig. 3. This process can be explained using the concept of siphoning.

The curvilinear shape of the meander bend acts to drive the process of siphoning and its input energy comes from the level difference of points A and C (due to longitudinal slope of the channel), similar to the difference of water levels in siphoning. This additional energy would take the channel to meander up to the point D. Similarly, the process can be extended to points E, F, and so on. Therefore, it can be inferred that the expanding meanders are the result of longitudinal slope of the channel.

The expansion of alluvial meanders can be described in terms of angle β (Fig. 3). Using elementary trigonometry, angle β can be related to the Strauhal number, S_t, as:

$$\frac{1+\tan\beta/2}{1-\tan\beta/2} \qquad (3)$$

Since the Strauhal number is taken as a universal constant, the tangent of angle β should exhibit a characteristic of the process of meandering in a river system.

3.3 Evolution of Cut-Off

The process of cut-off in meandering can be described as follows. As indicated above, the water through the process of siphoning can be elevated only to a certain extent, which depends on the total flow resistance exerted by the pipe wall. As soon as the total resistance exerted by the bed material in the channel portion, for example EFG (Fig. 3), equals the driving input flow energy due to the initial velocity at point D, lateral slope, and siphoning, the flow velocity will reduce to zero at point F, leading to a discontinuity in flow. Consequently, the impounding will occur at point E and the water will automatically start flowing in the direction of channel gradient (from E to G), which is the point of cut-off.

The development of a cut-off also helps describe the point of reference to measure the length of channel for computing the tortuosity ratio that reflects meandering characteristics. For determining the length of natural rivers, there often exists an uncertainty in specifying the length of the channel. To this end, the point of start of meandering or the beginning of a cut-off should be taken as a reference point and the length should be considered up to the point of beginning of the subsequent cut-off.

4. EXPERIMENTAL SET-UP AND PROCEDURE

A movable laboratory channel with varying slope was installed for an experimental study of the meander planform development. Measurements of deformation of the meandering channel along with the observations of discharge and slope of the main channel were taken. The main channel, as shown in Fig. 5, was 10.00 meter long, 1.60 meter wide and 0.42 meter deep. There was a movable carriage (8.80 meter long) on the side rails, which was used to set the profile indicator instrument and the velocity measurement instrument for obtaining the geomorphological and physical characteristics of the meandering channel. Water coming from the head tank passed through the water tranquilizer (1.60 meter wide and 0.26 meter long and 0.65

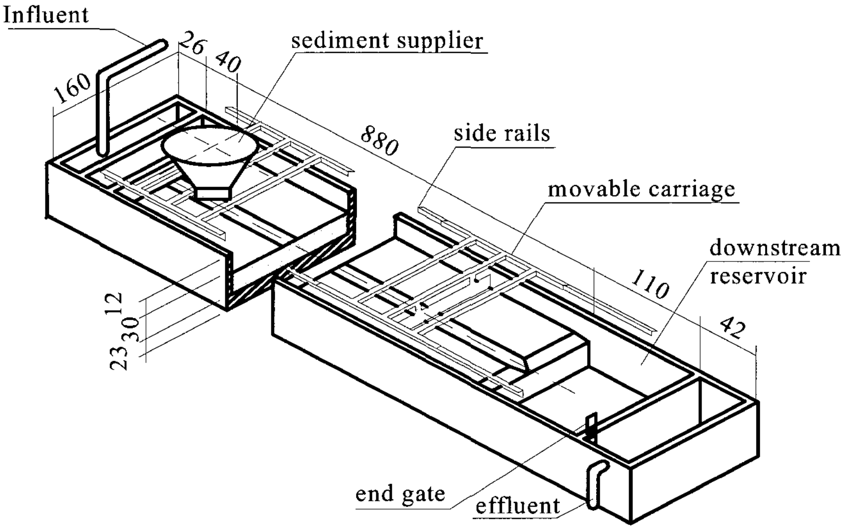

Fig. 3. Schematic View of the Experimental Set-up (all dimensions in cm)

meter deep). The downstream reservoir for outflow with the end gate was 1.10 meter long, 1.60 meter wide, and 0.65 meter deep. For every run, it was easy to change the slope, the discharge, and other parameters using the laboratory channel with variable slope.

Tests were conducted in the initially straight channel which was artificially carved in the uniform sandy material. A constant rate of flow was passed which was sufficient to move the sand along the bed and to erode the channel banks. The sediment supplier for the feedback system was placed at the entrance after the tranquilizer. The sand collector, 0.42 m x 1.60m x 0.65m, was kept at the end of the channel. The water carrying channel on the laboratory alluvial bed 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 wide and 0.15 meter high. No sand was fed at the entrance of the stream.

Following preliminary experimental results, experiments with proper discharge and slope combinations were planned. Also, additional experiments were conducted to check the repeatability of meander tests and to examine the meander performance at the extremes of steep and flat slopes. For each test, the flume had to be prepared at the beginning. This was done according to the following procedure. (1) The bed material throughout the whole flume was loosened. It was necessary because the sand could otherwise 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 initially straight channel. (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 the water flow.

5. EXPERIMENTAL OBSERVATIONS AND THEIR ANALYSIS

This section presents the experimental observations and their analysis with respect to (a) how close the experimental set-up has been to the prototype for practical purposes, (b) how the tortuosity ratios generally used for describing the meandering characteristics are linked to each other, and (c) how phase lag and flow regime, described by the Froude and Reynolds numbers, are related to each other .

5.1 Meandering in Artificial and Prototype Channels

The photographs of the fully developed meanders (Fig. 6) show that the laboratory stream developed naturally. An equilibrium condition was reached at the laboratory meandering channel after 72 hours from the beginning of measurements. Like an original prototype, the feedback of sand took place at the entrance of the sand reservoir of the main channel. Throughout the duration of tests, the stream constantly shifted its path of flow. It is noted in the photographs that the degree of meandering increased downstream. Thus, 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.

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, R_e is the Reynolds number, MBN is the number of peaks and troughs of the meandering channel, L is the straight channel length, LR is the meander bend length, and MB is the largest meander bend migration. Fig. 4 describes these terms as well as the central angle θ of a typical meander bend. In Table 1, the ratio L/LR is the tortuosity number, which describes the tortuosity of a 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. F_o was determined using the velocity and depth measured at the extreme upstream end of the channel, R_e is computed using the kinematic viscosity of water equal to 1.57×10^{-5} m^2/s which corresponds to the standard temperature and pressure. MBN represents the number of meander bends that occurred in the initially straight channel after 72 hrs of experimentation. The resulting forms of the meandered channel in the four experiments are shown in Figs. 7a-d, which correspond to experiments no. 1 through 4, respectively.

It is apparent from Table 1 that MBN generally increases with the increase in either F_o or R_e

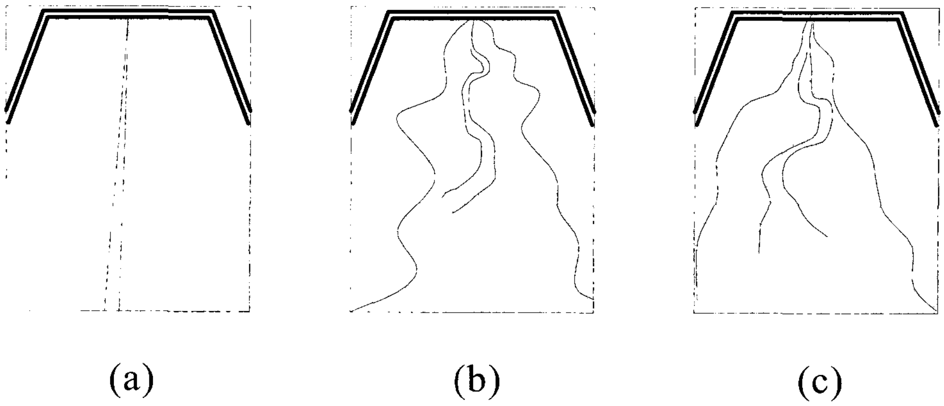

Fig. 6. Development of Meandering Channel: (a) initial channel, (b) meandering channel after 48 hrs., and (c) meandering channel after 72 hrs.

Table 1. Meandering Characteristics of the Laboratory Channel

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	10	2177	0.229	32.1
2	500	0.20	0.10	0.010	3165	4	535	0.934	4.2
3	500	0.40	0.20	0.020	6329	4	558	0.896	5.3
4	500	0.50	0.35	0.025	7911	9	1898	0.263	27.0

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 2. Meandering Characteristics of Some Natural Meandering Rivers

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 miles
Potomac	West Virginia	-	3	6.63	14.25	0.465	1.5 miles
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 and vice versa. It implies that MBN depends on the flow regime described by the Froude and Reynolds numbers. It is seen from this table that the tortuosity ratio L/LR decreases with the increase in either F_0 or R_e and vice versa. It infers that the flow in the regime of low velocity and high depths allows an alluvial channel to meander less than in an otherwise situation. It is noted that experiments 1 and 4 exhibit L/LR ratio as 0.229 and 0.263, respectively. On the other hand, experiments 2 and 3 show the ratio to be 0.934 and 0.896, respectively. Such a wide range of L/LR variation in these two sets of experiments indicates the existence of another factor governing the process of meandering besides the flow regime, described by F_0 and R_e. One of the governing factors might be the level of compaction. Due to the lack of measurements, it is difficult to quantitatively ascertain its impact on channel meandering. The level of compaction is largely governed by the initial moisture content of a sand material. Therefore, it is necessary to explain the moisture conditions of the sand material in different experiments. Since the required amount of sand material (of the order of 13 tonnes) was quite high, the same material was used in all the four experiments. The material was quite moist when experiments 1 and 4 were conducted and it was quite dry when experiments 2 and 3 were taken up. Since the moisture level was different in various experiments, the level of compaction due to the rearrangement of sand particles and soil moisture might be quite different in these experiments. The level of compaction increases the resistance to erosion, which is explained later.

To show how the above results match with those derived from natural river systems, a comparison is made with the meandering characteristics of some rivers in the United States, shown in Table 2. It is apparent from Tables 1 and 2 that the tortuosity ratio L/LR for laboratory channel (Table 1) varies from 0.229 to 0.934 and it ranges from 0.035 to 0.582 in natural rivers, implying that both the laboratory and many natural rivers meander more or less similarly and, therefore, support the above-said resemblance of the laboratory channel with the prototype. It is, however, noted that the boundary conditions also affect river meandering. Laboratory channels are usually of restricted geometry (length and width) whereas the natural rivers are not. The controlled conditions observed in the laboratory tests may or may not be realizable in the field. Channel characteristics connected with the meander geometry may also affect the process of meandering. 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 a 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, 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.

5.2 Link among ML/R, ML/MB, and LR/ML Ratios

To exhibit a link among the ratios used for description of meandering, it is necessary to investigate the individual meander bends, as illustrated in Fig. 4, of all the four experiments based on Fig. 7 and Table 3, as follows. In this table, the location describes the location of a meandering bend, whose number increases in the direction of flow. Other columns describe

Table 3. Detailed Features of the Meanders in Four Experiments

MB No.	ML(cm)	MB(mm)	R (mm)	*ML/MB	*ML/R	LR(cm)	*LR/(MB)
Experiment No. 1							
1	37.20	22.53	11.27	16.53	32.92	55.81	24.77
2	31.62	22.53	11.27	16.53	28.06	48.37	21.47
3	26.04	36.62	18.31	7.11	14.23	63.25	17.28
4	33.48	67.61	33.81	4.95	9.90	115.34	17.06
5	40.92	104.23	52.12	3.93	7.85	145.12	13.92
6	40.92	140.85	70.43	2.90	5.81	189.77	13.48
7	48.36	177.47	88.74	2.73	5.44	230.69	12.99
8	63.24	219.73	109.87	2.88	5.76	301.40	13.72
9	48.36	261.98	130.99	1.85	3.69	346.04	13.21
10	66.96	321.14	160.57	2.09	4.17	427.90	13.32
Experiment No. 2							
1	79.05	21.13	10.57	37.41	74.79	81.39	38.52
2	48.83	21.13	10.57	23.11	46.19	53.49	25.31
3	86.03	24.65	12.33	34.90	69.77	95.35	38.68
4	172.05	42.25	21.13	40.72	81.42	181.40	42.93
Experiment No. 3							
1	90.68	31.69	15.85	28.61	57.21	106.9	33.73
2	46.5	28.17	14.09	16.51	33.00	62.79	22.29
3	81.38	35.21	17.61	23.11	46.21	95.34	27.08
4	179.03	52.82	26.41	33.89	67.78	190.70	36.103
Experiment No. 4							
1	27.90	19.72	9.86	14.15	28.30	37.21	18.87
2	31.62	30.99	15.49	10.20	20.41	59.53	19.21
3	26.78	45.07	22.54	5.94	11.88	70.70	15.69
4	35.34	81.69	40.85	4.33	8.65	111.63	13.67
5	39.06	112.68	56.34	3.47	6.93	160.00	14.19
6	40.92	152.12	76.06	2.69	5.38	208.40	13.70
7	48.36	185.92	92.96	2.60	5.20	253.02	13.61
8	63.24	230.99	115.49	2.74	5.48	308.84	13.37
9	52.08	270.43	135.22	1.93	3.85	372.09	13.76

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

Table 4. Parameters of the Relations(EQ. 4)

Ratio	Experiment 1			Experiment 2			Experiment 3			Experiment 4		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
ML/R	51.64	-1.39	0.99	-244	329	0.33	-119	193	0.88	40.36	-1.24	0.99
ML/MB	28.06	-1.44	0.99	122.1	165	0.33	-59.6	96.7	0.87	20.17	-1.24	0.99

the corresponding ML, MB, R, and LR of the meandering bend. It is seen that, in all four experiments, ML and 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. 8 that shows the enveloping curves for meander formations during the four experiments. Thus, the meandering behavior of the laboratory channel expands in the direction of flow, similar to natural rivers.

Based on the data of Table 3 and Fig. 7, the three tortuosity ratios, ML/MB, ML/R, and LR/ML, are plotted against each other in Fig. 9. For a meander bend, the ratio LR/ML is equivalent to the inverse of the above described L/LR ratio. The plots of Fig. 9 exhibit relations of the form:

$$Y = aX + b \tag{4}$$

where Y is the ML/R or ML/MB ratio, X is the LR/ML ratio, and a and b are the coefficient and exponent, respectively. The variation of these parameters is shown in Table 4. In this table, r^2 is the coefficient of determination. It is seen that experiments 1 and 4 exhibit a strong relationship among these ratios, with $r^2 = 0.99$, which is close to 1. Experiment 3 exhibits a sufficiently high r^2-value (= 0.90), whereas experiment 2 yields a very low r^2-value (= 0.33), because this meander development did not come to an equilibrium phase. In general, ratios ML/R and ML/MB decrease with an increase in the value of the LR/ML ratio. It is interesting to note that exponent 'b' for both ML/R and ML/MB ratios assumes the same value in experiments 2-4, and the values in experiment 1 are in a close range of (-1.39, -1.44). It implies that the rate of decay (or decay pattern of both the ML/R and ML/MB ratios with the LR/ML ratio) is the same. Similarly, parameter 'a' for the ML/MB ratio is almost half of the ML/R ratio in all the four experiments. It infers that the ML/R ratio is approximately twice the ML/MB ratio for a given LR/ML value. Thus, it is possible to use any of these ratios to describe the process of river meandering.

5.3 Relation between Phase Lag and Flow Regime

As shown in Fig. 8, the channel meanders with different phases, depending on the flow regime. To describe this characteristic, the phase lag is defined as:

$$\phi = \frac{2\pi}{ML}\Delta x \tag{5}$$

where ϕ is the phase lag in radian, ML is the same as described in Fig. 4, and Δx is the longitudinal distance between two peaks or troughs of meandering bends. Eq. 5 is similar to that proposed by Mishra and Seth (1996) for de-

Table 5. Computation of Phase Lag Between Experiments 1 & 4 AND 2 & 3

MB No.	Experiments 1 & 4					Experiments 2 & 3				
	Average ML (cm)	x of Exp. 1 (cm)	x of Exp. 4 (cm)	Δx (cm)	ϕ (rad.)	Average ML (cm)	x of Exp. 2 (cm)	x of Exp. 3 (cm)	Δx (cm)	ϕ (rad.)
1	32.55	18.61	18.61	0.0	0.000	84.87	39.54	46.52	6.98	0.516
2	31.62	55.82	48.37	7.45	1.479	47.67	100.02	109.32	9.30	1.225
3	26.41	89.13	78.14	11.16	2.654	83.71	181.43	190.73	9.30	0.697
4	34.41	119.07	107.91	11.16	2.037	175.54	311.68	318.06	6.98	0.250
5	39.99	160.00	148.84	11.16	1.753					
6	40.92	200.93	189.77	11.16	1.713					
7	48.36	241.86	230.70	11.16	1.450					
8	63.24	301.40	290.24	11.16	1.108					
9	50.22	360.94	349.77	11.16	1.396					

NOTE: Average ML represents the average value of ML of the same bend number in two experiments, x represents the distance from origin to the peak or trough of a bend, Δx is the difference of x-values in two experiments, and ϕ is the phase lag of the same bend no. in two experiments.

scribing the phase lag of the waves occurring in open channel flows. The computed phase lags between the meandering patterns for the two sets of experiments 1 & 4 and 2 & 3 (Fig. 8) are shown in Table 5. In this table, the average ML represents the average value of ML of the same bend number in the experiments considered for the phase lag, x represents the distance from the origin to the peak or trough of a bend, Δx is the difference of x-values observed in two experiments, and ϕ is the phase lag of the same bend number in two experiments. It is seen that the meandering pattern of experiment 4 precedes that generated by experiment 1 and similarly, the meandering pattern of experiment 2 precedes that generated by experiment 3. In both sets of experiments, the phase lag first increases with distance measured from the point of origin in the direction of flow, reaches a maximum value, and then decreases gradually. The average phase lag of the set consisting of experiments 1 & 4 is equal to 1.51 radians, whereas it equals 0.672 radian in experiments 2 & 3. The high difference in the average value of these phase lags can be attributed to the difference between the levels of compaction in the two sets of experiments due to the initial moisture of the sand. Here, it is noted that this phase lag differs from that between flow path and channel center-line, generally used for describing the process of meandering in alluvial rivers (Chang, 1988).

6. VERIFICATION OF THE BUCKLING AND SIPHONING CONCEPTS

6.1 Verification of Buckling Concept

As mentioned above, the artificial laboratory channel in each experimental run was initially straight, which, after a time, developed to follow a meandering path. To first describe the evolution of a meander as to why the channel followed a particular path and not the reverse, an analogy with the above buckling of a column under eccentric loading can be considered. As seen in Fig. 7, the right bank of the channel is first eroded in all experimental runs. Since the system of inflow supply has been the same in all experiments, the velocity distribution across the cross-section at the beginning of the channel has been the same. It implies that the direction of flow eccentricity has been towards the left bank of the channel, leading to the erosion of the right bank of the channel, similar to the buckling of the column in the opposite direction of the eccentricity. Since the channel has been eroded to produce the meandering planforms, the flow velocities have been sufficient to counter the resistance of the bed material, as also stated in the experimental procedure.

As indicated earlier, a moist sand exerts more resistance to erosion than does a dry sand, because moist sand in the laboratory channel with laboratory channel walls limitations behaves as if it had very cohesive characteristics. That is why experiments 1 and 4 exhibit greater resistance to erosion than do experiments 2 and 3. Thus, the value of MB of the first meander bend in the latter experiments is greater than that in the former experiments. The ML value will, however, depend on the initial value of the Froude number (or initial flow regime) of the flow. In literature, ML is shown to depend on the channel cross-section characteristics (Chang, 1988), similar to the above described transverse length scale, B, of the inviscid fluid jet. The flow of high Froude number, referring to high flow velocity, is likely to produce more acute bends than the flow of low Froude number and vice versa, similar to the shape of the buckled column; the higher the Froude number, the greater is the number of bends (MBN) and vice versa (Table 1).

6.2 Verification of Siphoning Concept

In meandering, the laboratory channels expand in the direction of flow, as shown in Fig. 8. To support the viability of the concept of siphoning, the meander bend migration (MB) of the first bend is taken to drive the process of siphoning, for it depends on the longitudinal slope of the channel. The observed MB-values (Table 3) are plotted against the difference between the half of LR of the following meander bend and the bend under consideration, as shown in Fig. 10 for all the experiments. It is apparent that both Figs. 10a & b exhibit a rising trend of ΔLR with MB. Furthermore, for a given MB, ΔLR for experiment 1 is generally less than that for experiment 4, implying that the bed material in experiment 1 was less resistant than in experiment 4. In other words, sand was drier in experiment 1 than in experiment 4. Similar inferences can be drawn for experiments 2 and 3. The sand in experiment 2 was drier than in experiment 3. On similar grounds, the sand in experiments 2 and 3 was drier than in experiments 1 and 4. On the whole, a consistent trend of all the four experiments underscores the validity of the siphoning concept.

From Fig. 8 the angle β is of the order of 38.42 degrees for experiments 1 and 4 and it is equal to 8.81 for experiments 2 and 3. The corresponding Strauhal numbers for these two sets of experiments can be computed from Eq. 3 as equal to 2.07 and 1.17, respectively. The difference in these numbers can be attributed to the level of compaction or moisture content of the sand material. The higher Strauhal number corresponds to the more resistant (or more moist) sand material and vice versa.

CONCLUSIONS

The following conclusions are drawn from the study:

1. The characteristics of meandering in the laboratory channel were quite close to those observed in the field.
2. There exists a relationship between three tortuosity ratios described as ML/R,

ML/MB, and LR/ML ratios. For example, ML/R is approximately twice the ratio ML/MB for a given LR/ML value

3. The concept of buckling is useful in describing the evolution and acuteness of meandering in a river.
4. The concept of siphoning supported by the laboratory observations describes the expansion of the meandering pattern of a river in the direction of flow. This concept also helps describe the process of cut-off to aid the description of the river length for determining tortuosity ratio.
5. The more resistant sand materials exhibit the higher Strauhal numbers in meandering and vice versa.

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