Modeling high sinuosity meanders in a small flume

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Received 10 September 1997; revised 9 November 1997; accepted 6 December 1997

Abstract

Meandering channels with exposed point bars and sinuosities near 2.0 can spontaneously develop in a mix of diatomaceous earth and kaolinite clay. The experimental streams that were studied were as small as 4 cm wide. They showed many of the characteristics found in large meandering streams such as migration of channels, formation of point bars, clay plugs, chutes and bar scrolls. Most of the meander series began as a first sharp bend that induced subsequent bends downstream. Sediment transport, specifically bed load, together with the slope of the floodplain, were the dominant influences, if not the cause of the channel instabilities that led to channel migration and bend formation. Bank cohesion allowed migrating channels to assume sinuous shapes and to maintain fairly uniform widths. The experiments were conducted in a small flume and used simple equipment. The use of light, fine grained materials in flume experiments may prove to be valuable in learning more about the conditions of soil, slope and flow which produce various meandering planforms.

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Keywords: meanders; flume studies; modeling; braided streams

1. Introduction

Examples of meandering patterns are common among natural streams, but the reproduction of well defined, highly sinuous channels in laboratory flumes has proved elusive. Though much knowledge has been gained from earlier flume studies, such as Tiffany and Nelson (1939), Friedkin (1945) and Schumm and Kahn (1972), the resulting channel patterns have been acknowledged as being generally straight with a sinuous thalweg.

Perhaps the most successful recent attempt to model high sinuosity river meanders has come from Jin and Schumm (1986). They used a floodplain made of a base of sand and topped with a layer of kaolinite clay and fine sand. Because of their progress, experiments were developed to explore additional techniques that could be useful in modeling meanders in a laboratory environment. This paper presents the results of experiments that simulated the formation of well defined, highly sinuous meanders in a small flume using light, fine grained materials.

2. Experiments

The experiments were conducted in a flume 3 m long and 1.2 m wide that had wooden sides, a plywood base and was lined with a removable plastic tarpaulin. The frame of the flume had a hinge near...
the midpoint for adjustment of the slope. The water was circulated by small pump, with discharge levels being determined by volume per time measurements. Sediment combinations used in the experiments have included rock flour with kaolinite, cornstarch, cornstarch with calcined white China clay (CWC), diatomaceous earth (DE), and perhaps the most successful to date, diatomaceous earth with calcined white China clay (DE + CWC).

The experimental materials all had a powder-like consistency. Particle sizes for kaolinite, rock flour and CWC were distributed in the 4 to 10 μm range. The cornstarch grains averaged 12 μm in diameter with a 4 μm standard deviation. The range of sizes for DE was considerably wider than the other materials. The mean diameter for separate particles was estimated to be 35 μm with a standard deviation of 14 μm. Because of surface roughness, the individual diatoms could interlock to form loose clusters that were 100 μm or more in size.

The sediments were chosen to scale down the alluvial properties needed for meanders to form in the reduced flows of a flume. The intent of the low density and fine grain size of the materials was to facilitate transport, especially to the shallows of incipient point bars. To ensure enough cross-sectional strength in the channel to support curves and lateral reaches, bank cohesion is needed. A binding agent such as clay is necessary, as was indicated by the studies of Schumm (1960). But the cohesion must not be so strong as to stop erosion entirely. For small flows, CWC clay seemed a good choice, being less sticky than other types of kaolinite.

For comparison, the wetted densities of selected alluvial combinations are shown in Table 1. Wetted density is defined as the mass per volume with water added to form the sediment consistency of an experimental run. Table 2 lists typical values for experimental parameters. Included are the flow, slope, and velocity levels, (Q, slope and u), which produced the most sinuous patterns with well defined channels. The parameter d is the mean measured depth of the channel and g is the constant for gravity. The corresponding Froude and Reynolds numbers have been calculated.

A typical run was started by mixing the sediment components in the desired ratios. The mixture was then premoistened and smoothed in the flume. A straight initial channel was created, the slope adjusted and the water flow started. The water was introduced without an initial bend at levels between 5 and 50 ml/s. For most runs, flow was kept at a constant, or bankfull level. For some tests it was decreased or increased for periods of days to study the effects on planform. An hour or two after the start of an experiment, after the stream had established its initial channel, moist sediment was added at the stream head by hand twice per day at roughly 12-h intervals. It was arranged in small heaps to either side of the water inlet so as to erode gradually into the stream over several hours.

The intermittent method of the sediment supply had no observable effect on whether the stream meandered or not for the featured alluvial combinations. In several instances, a meandering pattern required only a few hours to develop. Under such conditions of continuous observation, the sediment flow could be kept reasonably constant. It was much more important that the sediment levels within the stream were sufficient to promote channel instability without causing the stream to overflow its banks.

<table>
<thead>
<tr>
<th>Material</th>
<th>Wetted density specific gravity</th>
<th>Mixture (% mass of tot.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>1.0</td>
<td>~</td>
</tr>
<tr>
<td>rock flour + kaolinite</td>
<td>1.82</td>
<td>kaol. 15%</td>
</tr>
<tr>
<td>cornstarch + CWC clay</td>
<td>1.28</td>
<td>CWC 20%</td>
</tr>
<tr>
<td>DE + CWC clay</td>
<td>1.35</td>
<td>CWC 30%</td>
</tr>
<tr>
<td>(diatomaceous earth + clay)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

Experimental parameters of the stream flow

<table>
<thead>
<tr>
<th></th>
<th>DE + CWC</th>
<th>Cornstarch + CWC</th>
<th>Rock flour + kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (ml/s)</td>
<td>9</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>slope</td>
<td>0.015</td>
<td>0.020</td>
<td>0.025</td>
</tr>
<tr>
<td>u (cm/s)</td>
<td>15–20</td>
<td>18–22</td>
<td>18–25</td>
</tr>
<tr>
<td>d (cm)</td>
<td>~ 0.5</td>
<td>~ 0.5</td>
<td>~ 0.7</td>
</tr>
<tr>
<td>Froude # (u/√(gd))</td>
<td>0.68–0.91</td>
<td>0.82–1.00</td>
<td>0.69–0.95</td>
</tr>
<tr>
<td>Reynolds # (ud/visc)</td>
<td>750–1000</td>
<td>900–1100</td>
<td>1250–1750</td>
</tr>
</tbody>
</table>
The transported sediment that reached the foot of the flume was allowed to move down the drain with the water to a collection tank. By measuring the amount of sediment in the collection tank, the typical flow of sediment was shown to average 10 ml/h for the experiment shown in Figs. 1 and 2.

While some of the runs needed only a few hours to begin meandering, others, such as those using rock flour, required two to three weeks. Even for the DE + CWC mixture, a week or more might be needed for the stream to create a flood plain of sufficient breadth (4–8 channel widths) and consistency to support meander formation. Given a sufficient slope and sediment supply, any of the experimental mixes having enough cohesion to maintain a well defined, single thread channel, were likely to produce high sinuosity bends.

3. Results

The mixtures, rock flour + kaolinite, cornstarch + CWC, and DE + CWC were all effective in producing well defined channels and meanders in a small flume. The most effective at producing a series of meanders has been the DE + CWC combination mixed in a ratio of 5:2 by weight. The slope was near 0.015. Experience indicates considerable leeway in the allowable CWC percentage. Ratios of 5:1 to 2:1 worked well for discharge levels of about 8–25 ml/s. Photographs of the various stages of one of the more successful runs are shown in Figs. 1 and 2.

A distinguishing feature of these experiments was the development of deeps and shallows related to the channel curves and crossings. The pools of the curves are the deepest parts of the system as shown by the profile in Fig. 3a. The related map, Fig. 3b, shows the locations of the pools.

Along the channel, the average distance between pools was 15 cm, in the example shown. Given a channel width of 4 cm, the pool spacing is about 4 widths, which somewhat smaller than the 5–7 widths often seen in rivers, as described in Leopold et al. (1964).

The measured cross sections of the channel are shown in Fig. 4a, with the respective locations in Fig. 4b. The thalweg is offset from the centerline in the direction toward the concave bank. The asymmetry is not as pronounced as is usual for natural streams. In Fig. 4a a few morphologic features often associated with meandering streams are indicated. Labeled are portions of abandoned channels, clay plugs, scrolls on points bars and an example of a concave bank bench.

3.1. Formation of point bars

The build up of point bars resulted almost entirely from bed load. Often, the channel was broader and shallower on its approach to a bend with the bulk of the sediment flow moving along the inside of the turn. The presence of the sediment train took up space within the channel and shifted the water flow slightly toward the opposite bank, enhancing erosion there. The process was similar to one that has been described by Dietrich and Smith (1984). As the outer bank eroded, even by a few millimeters, grains of the sediment could be seen coming to rest on the bar. Bank migration continued. The water flowing over the edge of the point bar gradually became shallower until particle movement on the margin of the bar was no longer evident. Over time, the local water level continued to subside leaving part of the new deposit above water. The mechanism by which the subsidence took place was not readily apparent. Possible causes could include channel deepening near the bar or slight changes in slope because of local degradation or aggradation. Bar deposition could be slow and steady but was often episodic in nature, manifest by the growth of dune-like structures along the bar margin.

For the pictured experiment, exposure of a centimeter wide lens of bar could take from less than an hour to as long as a week. Whether by dune or steady accretion, bar stabilization was dependent on channel migration away from the bar. The resulting decreased flow of water over the bar was necessary for sediment adhesion and consolidation.

An example of a point bar slow in emerging is seen in Fig. 2c, indicated by the arrow. Most of the bar remained under water for approximately 120 h, even though it was covered by a steady flow of sediment. Fig. 1b shows that the radius of the adjacent bend of the channel eventually enlarged enough to lower the water level slightly, halting sediment movement and exposing the bar.
Fig. 1. (a,b,c) Three photographs showing a series of meanders that formed in a mixture of diatomaceous earth and calcined white China clay. After approximately 500 h, the flow was stopped to obtain profile data. Channel migration had slowed to virtually nothing after the first 250 h. The planform appeared to be near a state of static equilibrium. In (a), a broad view of the stream channel. Flow is toward the viewer. The measuring scale is 30.48 cm (1 ft) in length. (b) shows a close-up view of the channel section under study. (c) provides a more detailed view of the meandering channel. The flow goes from left to right.
Suspended load, seen largely as water turbidity, did not contribute much to the overall height of the point bars. It did, however, help secure point bar sediments already in place. Usually, as the flow of water over a new deposit ebbed, the deposit became grayer as clay gradually settled upon it—or percolated up through it. The clay appeared to give deposits a hysteresis-like quality. The shear stress needed to erode a stabilized bar was observed to be higher than that needed to create it initially. Erosion resistant deposits can more readily deflect the water flow laterally across the valley slope, enhancing stream sinuosity. It is possible that suspended clay, moving into the sediment matrix, makes the point bars more durable.

Evidence in the literature that supports the idea of hysteresis, can be found in the studies of cohesive deposits found in estuaries. Partheniades (1965); Parchure and Mehta (1985); Mehta et al. (1989) and others discuss in detail the processes of deposition and consolidation for cohesive sediments. The figures in Nicholson and O’Connor (1986) clearly illustrate how consolidation increases the resistance of deposits to subsequent erosion. Similar reports, published specifically for river systems, are harder to find. When mentioned, consolidation effects are discussed only briefly, as in Section 9 of Parker (1978).

Suspended load was important in the creation of the clay plugs that formed across sections of slack water adjoining the main channel. Examples of clay plugs are labeled in Fig. 4b. Accretion was slow, taking a week or more to approach the water surface. Deposits were medium gray in appearance indicating high clay and low DE content in contrast to the more tan shade of mixed sediments. Once in place, the plugs were tougher to erode than bars.

3.2. General scenario for meander formation

The general sequence of meander development for DE, rock flour and cornstarch is shown in Fig. 5. The progression of the pattern is similar to that of an experiment, involving surface tension meanders, described in Davies and Tinker (1984) and illustrated
Fig. 2. (a,b,c) Shown are the earlier stages of the same experiment depicted in Fig. 1. They show in part the development of the meandering pattern over time. (a) shows the experiment nine hours after start and two hours after the initial kink at the upper right had caused the next bend downstream to form. (b) shows the channel four hours after the onset of meandering. (c) shows the planform about 120 h after meandering first began. The bar, indicated by the arrow, is still largely inundated. An additional 50 h were required for the bend to shift laterally enough for the bar to emerge above water.

by Fig. 2a–e in that paper. For the present experiments, the usual chain of events began with a reach of the initially straight channel drifting laterally as a result of shoaling along one bank. The shoal itself might be from 7 to over 25 channel widths in length. A kink in the channel gradually formed that became larger and more acute as the flow eroded into the bank. The bank material, because of clay content, was resistant enough to deflect the flow in a cross slope direction, creating a growing bend opposite the initial kink. The new bend in turn enlarged enough to induce another bend down slope and so on. As the sequence grew, the bends increased in amplitude and wave length. Repeated trials indicated that only one kink was necessary to produce a meander sequence.

The observed shoaling mechanism may be connected with 'highly elongated, partially beached oblique dunes' referred to in Parker (1996). Parker suggested that such dunes give rise to the scrolls often seen on point bars. In the present experiments, dune-like structures were sometimes seen; a number of point bars did have a scroll-like appearance.

3.3. More observations for various alluvial combinations

In the cases of rock flour and DE the individual meander loops tend to become asymmetrical in shape, but in the opposite sense to those of Davies and Tinker (1984) and Parker et al. (1982). They are convex in the upslope direction but still tend to migrate downslope.

In the pictured experiment with DE + CWC, stream migration was most rapid right after the meander sequence began to form, but slowed gradually over time. It took about 180 h from the formation of the initial kink to what looked to be full
sequence amplitude. At this point, even significant increases to sediment load only resulted in slight, localized changes. Sediment continued to flow but without much effect. Given the constant flow of water, the stream appeared to be in a state near static equilibrium.
Bends in rock flour + kaolinite formed much more slowly, even though higher flow levels of 45 ml/s were used. Steeper slopes were required to create a well defined channel, typically around 0.025. Many bends had an abrupt, sawtooth appearance. Nevertheless, after a month, a loop with a goose neck formed before the run was discontinued. Though no alternate bar series were seen, the bed in places contained shallow pools spaced from 1 to 5 channel widths apart. They were not as deep as pools at bends and

Fig. 4. (a) Channel cross sections measured at various points along stream. The direction of water flow is into the page. The average width to depth ratio is around 5, well below the minimum value of 10 considered necessary for alternate bar formation. (b) The locations of the cross sections. They were chosen to show channel shape along typical straight and curved reaches. Also labeled are structures of interest often associated with meandering streams.
looked similar to those described by Keller and Melhorn (1973). The presence of the pools did not have a perceptible effect on planform changes.

3.4. The effect of the slope of the floodplain on channel pattern

The experiments made clear that sufficient longitudinal slope was necessary for well defined meandering channels to form. The slope of the floodplain needed to be steep enough to promote channelization and channel instabilities, but not so steep as to induce braiding. This requirement agrees with the experimental findings of Schumm and Kahn (1972) as well as the field work of Schumm et al. (1972) and Martinson (1983). After a considerable number of trials, slopes of around 0.015 were found to work well for lighter the sediments, such as cornstarch and diatomaceous earth. For denser materials, such as rock flour, steeper slopes of around 0.020 to 0.025 were usually needed. If the slope were too shallow, the resulting pattern could vary from a water flow that spread out over the floodplain, to wide non-uniform channels, to channels that were fairly well defined and transported sediment, but were of low sinuosity and prone to bifurcation.

3.5. The role of sediment flow in meander formation

In addition to the slope of the floodplain, sediment flow provided the other key impetus for the instability that led to meander formation in the flume experiments. The shoaling that produced the initial kink required ongoing deposition from a supply of sediment, as did the subsequent growing point bars. When sediment no longer was introduced at the flume head, enlargement of meanders and evolution
of the planform soon slowed to imperceptibility. When sediment input was high enough, the channel width to depth ratio increased markedly and stream braiding resulted, similar to what was reported by Stebbings (1963). The most effective levels of sediment flow covered 60% to 80% of the channel bed on straight reaches but tended to keep to the inside half of the channel around the turns. Migration could take place while channel definition was maintained. Analytical treatments such as Parker (1976), have emphasized the primary role of sediment transport in stream meandering and braiding.

The presence of periodic alternate bars with 10 channel widths separation or less, often viewed as a precursor to meander development, was notably absent in the featured experiments. Deeps or pools could almost always be associated with the curve of a reach. The observed channel kinks may prove to be elongated forms of alternate bars. They occurred singularly however, with no discernible periodicity along the stream course. Moreover, the lengths of resulting meanders were much shorter, without apparent correlation to the reach length of the initial shoaling. In his field work, Ikeda (1989) has noted an absence of alternate bars in certain previously meandering streams that have been artificially straightened.

One explanation for the lack of recognizable alternate bar patterns during the experiments is the low width to depth ratios of most of the stream channels. A value of 10 or less has been common for alluvial mixes with clay content of greater than around 15%. In trials with low levels of cohesion, however, ratios of greater than 20 were observed. The sediment flow was high in both volume and velocity relative to other test runs. Though a tendency to braid was often evident, regular, near-periodic alternate bar patterns were not obvious in any of these channels.

3.6. Effects of the levels of water flow

For DE + CWC, meander geometries were in accord with the observations of Leopold and Maddock (1953) and others. At flow levels of 9 ml/s, meander wave lengths averaged a little over 8 channel widths. A value around 7 was common for the amplitude to width ratio. The values for Reynolds number were calculated from stream velocity and depth measurements and found to be in the 750–1000 range. Alluvial meandering does not require full turbulence to occur. The Froude numbers for all experiments were subcritical.

A limited range of water flow occurred for which the 5.2 DE + CWC mix would allow defined channels and meandering. If discharge were increased enough, braiding would result. Discharges below 25 ml/s produced fairly uniform channels. Point bars built up and emerged readily. At levels around 35 ml/s, meandering was still seen, but channel width became much less uniform, varying by a factor of 4 or more around bends. At still higher discharges, the stream course became even less well defined and sinuosity decreased. Multiple channels developed. The sediment cohesion was no longer sufficient to force the flow into a single thread channel.

4. Conclusion

The experiments described in this paper, though largely qualitative, demonstrate that high sinuosity meanders in alluvial media can be produced by small streams in a laboratory setting. Only simple equipment and combinations of low density, fine grained material are needed. The resulting planforms show many similarities and several differences in comparison to larger rivers. Similar attributes include scolled point bars, concave bank benches, clay plugs, etc. Differences are found in meander shape, much lower Reynolds numbers and slopes that are steeper than in most natural streams.

The experiments show how meanders can develop. They illustrate the importance of slope, sediment flow and sediment cohesiveness in the formation of meanders as well as in enabling a stream to maintain a well defined channel. Future work should more clearly quantify the role of cohesion in meander formation. Cohesion seems responsible for a ‘hysteresis effect’ with regard to observed sediment erosion, deposition and consolidation characteristics as channels migrate. The lack of a strong tendency for periodic alternate bar formation in the experiments could use some additional analysis. Explanations involving channel width to depth ratios alone are not sufficient.
Acknowledgements

The author wishes to thank Luna B. Leopold whose kind help and encouragement made this paper possible. And thanks also to Gary Parker and Chris Paola for their encouragement and discussions concerning the experiments.

References


