Hydraulic characteristics of meandering mobile bed compound channels

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The experimental arrangement for examining the hydraulic characteristics of overbank flows in a meandering mobile bed compound channel at the UK Flood Channel Facility (FCF) is described. The FCF was designed to bridge the gap between small and prototype scales and has been used in a series of experiments on straight compound, skewed and fixed-bed meandering channels. For the present study the sinusoidal meandering main channel had a mobile sand bed. Several overbank flows were measured with smooth or roughened floodplains. Floodplain roughness was provided by surface-penetrating rod elements. It was found that, for floodplain flows with a relative depth $>0{\cdot}2$, the average flow velocities over the floodplain, in the valley direction, were greater than in the meandering main channel. The principal main channel bedforms were repeating long dunes. There was also evidence of plunging flow over the main channel at the apex of bends.

Keywords: floods & floodworks; hydraulics & hydrodynamics; river engineering

Notation

B	top width of main channel
d	stage
L_m	path length of a full meander
l	path length to any point on meander
n	Manning's roughness coefficient
Q	discharge
$\boldsymbol{V}$	depth-average floodplain velocity component
Y_r	relative depth (= depth of flow on floodplain/total depth of flow)
θ	meander cross-over angle
θ_0	angle to main axis at any point on the sine wave
λ	Darcy–Weisbach friction factor

Subscripts

x	longitudinal (valley) direction
y	transverse direction
FP	floodplain
MC	main channel

Introduction

Rivers represent one of mankind's most important environmental assets. They are home to a splendid diversity of wildlife, provide water and wastewater facilities to urban populations, they give pleasure to many people and they enhance the landscape. River flows are often affected by man's activities and therefore require careful management for water supply, waste disposal, flood alleviation and power generation, as well as amenity uses.

2. While, previously, river design and management tended to be dominated by engineering concerns, there is now an increasing recognition that the conflicting pressures of engineering and ecological objectives must be rationalized and harmonized to ensure optimum use of a valuable resource. Thus river design is becoming more environmentally sensitive, seeking solutions which are sustainable and which enhance the ecological environment as well as meeting flood protection standards.

3. A flood alleviation solution which also offers environmental advantages is that of a two-stage or compound river geometry consisting of a deep main channel flanked by one or two floodplains. Such cross-sections ensure reasonable depths at low flows, which provide a suitable habitat for fish and other wildlife, while the floodplain areas provide both storage and additional conveyance during high flows.

4. The floodplain areas are, however, often developed for agricultural, commercial or housing purposes and this raises the issue of flood risk and flood protection. The assessment of flood discharge capacity and associated flood levels in compound river channels is uncertain. The flow patterns in such situations are complicated by interaction between flow in the central main channel and that over the floodplains. Added to this may be increased complexity of flow patterns due to variations in planform, such as meandering geometry which is common. Furthermore, bed and bank material may be fixed or erodible. Not surprisingly therefore, there is as yet no commonly accepted standard method for predicting discharge capacity in non-straight two-stage river channels.

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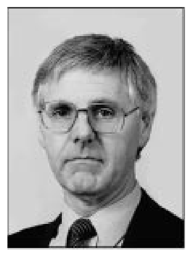

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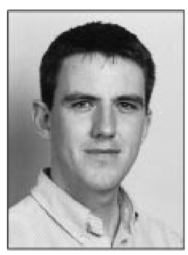

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Description of objectives

5. The objectives of this study are to

(*a*) describe a programme of research, using the UK flood channel facility (FCF), into the hydraulic behaviour of meandering mobile bed channels with uniform sediment
(*b*) relate this research to the long-term strategy of the UK FCF
(*c*) set the current programme in the wider context of compound channel research
(*d*) present the findings of the research programme relating to stage discharge relationships, velocity profiles, discharge ratios, flow resistance parameters and bedforms.

Straight compound channel flow

6. Compound channel flow is complicated by the existence of a region of turbulent shear at the interface between main channel and floodplain flows. This is due to the presence of a velocity gradient between the deeper and therefore faster-flowing main channel and the shallower and slower-moving floodplain areas. The effect is enhanced by the fact that floodplain roughness often significantly exceeds that in the main channel.

7. Differences in velocity give rise to the development of a momentum transfer mechanism between main channel and floodplain, which takes the form of a bank of vortices having vertical axes which form along each channel–floodplain interface. The mechanism retards channel velocity and discharge, while increasing the corresponding parameters on the floodplain. The net effect is a reduction of compound cross-section discharge when compared to that in a channel of simple cross-section at the same cross-sectional area and depth. Thus conventional methods of computing conveyance are not applicable to compound channels.

8. The first investigators to explore this momentum transfer mechanism were Sellin[1] and Zheleznyakov[2] who demonstrated by experimental means the presence of the vortices and their effect on velocity and discharge at overbank flows. There followed a number of similar small-scale laboratory studies aimed at exploring hydraulic parameters of overbank flow for various geometries and floodplain roughnesses. Myers and Elsawy,[3] Myers,[4] Knight and Demetriou[5] and Wormleaton *et al.*[6] were able to quantify the momentum transfer mechanism by measuring boundary shear stress distributions and applying the momentum equation to channel and floodplain zones. They showed that the apparent shear stress on the channel floodplain interface is many times greater than the average shear stress around the solid boundaries. Since the most commonly used methods of discharge estimation in compound channels depend on an assumption of zero shear at the interface, these studies illustrated the reasons why such methods are unreliable in such applications.

9. The main drawback of these studies was their small scale, since it was unclear as to how well they were modelling compound channel flow at prototype scale. Ideally, full-scale field experiments would be the best way to further understanding of flow structures in compound channels, as well as evolving accurate methods of discharge prediction. Some field studies have been undertaken by Martin and Myers[7] and Myers and Lyness[8] which have proved valuable in indicating values of flow resistance parameters at prototype scale. Field work is difficult partly because compound channel flow conditions occur typically under flood conditions when acquisition of data is difficult and sometimes dangerous. Another disadvantage is that only a few hydraulic parameters can be measured, namely depth, velocity and discharge, thus limiting the conclusions which can be drawn. Furthermore, field data may only safely be interpreted as relevant to the conditions under which they were collected, and should be generalized only with extreme caution.

The Flood Channel Facility

10. It was to offset the disadvantages of both small-scale measurements and field data acquisition that the United Kingdom FCF was conceived. The FCF was designed to bridge the gap between small and prototype scales while also providing a flexible environment where a wide-ranging generalized study of compound channel hydraulics could be undertaken. The conception of the FCF is presented by Knight and Sellin[9] who describe this large compound channel facility some 50 m by 10 m in overall dimension. Since 1986, when it was commissioned, the FCF has been used almost continuously for a planned and coordinated series of experiments involving collaboration between numerous academics both from within the UK and abroad.

11. Phase A of the FCF programme centred on straight and skewed fixed boundary compound channels, and the results of this have been presented by Myers and Brennan,[10] Knight and Shiono,[11] Wormleaton and Merritt[12] and Elliott and Sellin.[13] Phase B explored meandering planforms having fixed boundaries and has been reported by Sellin *et al.*,[14] Ervine *et al.*[15] and Greenhill and Sellin.[16] The data from Phases A and B have been presented in the form of a design guide for river engineers by Wark *et al.*[17]

12. The philosophy of the FCF programme was to progress from the simple to the more complex in terms of the conformity of the experimental arrangement to prototype rivers. The earlier studies were invaluable in elucidating fundamental flow patterns which could then be used to enhance understanding of more

complex arrangements. Planform complexity was increased from straight to skewed to meandering. Phase C therefore progressed further towards prototype conformity by introducing mobile boundaries, including both uniform and graded sediments. Phase C is currently under way, with straight and meandering planforms now complete, and with plans in hand to progress to self-formed compound channels in the near future. The present work described by the authors, on mobile bed compound channels, is confined to observations on hydraulic behaviour. Sediment transport measurements were also taken during the course of the experimental programme but observations relating to sediment transport will be described in a separate paper.

13. A promising recent development is the application of two-dimensional and three-dimensional turbulence models to compound channel flow as reported by Krishnappan and Lau,[18] Satish *et al.*[19] and Tominaga and Nezu.[20] Wark *et al.*[21] have attempted to apply a turbulence model to the prediction of discharge in both field and laboratory contexts, and have compared their findings with experimental data. Development of two- and three-dimensional turbulence models continues to represent a major thrust for compound channel research in the future. It presents the attractive prospect of a generalized methodology of compound channel analysis and design. To engender confidence in such approaches, however, there needs to be verification by comparison with extensive data from both laboratory and field.

Flow resistance in alluvial and meandering two-stage channels

14. Flow resistance for overbank flow in meandering compound channels with a mobile bed in the main channel is difficult to quantify. Flow resistance in the main channel with mobile bed material can be attributed to two sources, described by Chang[22] as grain resistance of the channel bed material and form resistance or form drag due to the shape of channel bedforms. The form resistance is usually several times larger than the grain resistance. Another representation of flow resistance in alluvial channels is possible and is described by Featherstone and Nalluri[23] as the total resistance approach. In this method, empirical formulae have been derived relating velocity to hydraulic radius and bed slope without splitting flow resistance into grain roughness and form roughness.

15. For flow in a meandering channel, extra flow resistance will arise because of energy losses in bends. Overbank flow in compound meandering channels adds a further degree of complexity and has been the subject of recent investigations by Willets and Hardwick,[24] Sellin *et al.*[14] and Ervine *et al.*[15] Willets and Hardwick,[24] found from model experiments that main channel sinuosity influenced conveyance and that channel/floodplain interaction depends on the cross-section geometry of the inner or main channel. Sellin *et al.*[14] report on experiments carried out at the FCF. They describe flow structures, principally a large secondary current cell at bends and water plunging from the floodplain into the main channel near the centreline of the floodplain system. Ervine *et al.*[15] discuss methods of quantifying flow conveyance in meandering compound channels. One method they describe as the 'hydromechanics approach' of quantifying the energy loss due to each source, the other is to apply a correction factor to theoretical estimates of discharge based on bed friction only.

16. This is a similar approach to that adopted by Ackers[25] for straight compound channels. The method uses a three-zone subdivision of the meandering compound channel. The three zones are: below bankfull in main channel, meander belt floodplain zone above bankfull of main channel, and outer floodplain zone beyond the meander belt. The major parameters influencing flow conveyance are taken as

(*a*) sinuosity of the main channel
(*b*) relative roughness of the floodplain boundary compared with the main channel
(*c*) aspect ratio of the main channel
(*d*) meander belt width relative to total floodway width
(*e*) relative depth of flow on floodplain compared with main channel
(*f*) the main channel cross-sectional shape, including side slope of the banks of the main channel
(*g*) floodplain topography, in particular the lateral slope of the floodplain.

17. In their conclusions, Ervine *et al.*[15] state that the conveyance of a meandering compound channel is significantly less than the estimate based on bed roughness. Non-bed friction losses can be often as great as total friction losses from the bed of the main channel and floodplains.

Experimental programme

18. All the experiments reported were undertaken at the FCF at HR Wallingford, UK. The 10 m flume width allows a variety of channels of different planform geometry, cross-sectional shape and boundary type to be built. The large-scale nature of the channel, with its maximum discharge capacity of $1{\cdot}08\,m^3/s$, permits the modelling of flows over the complete floodplain width at sufficient flow depth to produce fully developed turbulent flow.

19. The planform of the experimental inner channel consisted of two sine-generated curves defined by

$$\theta = \theta_0 \cos\left(2\pi \frac{l}{L_m}\right) \qquad (1)$$

This expression is generally accepted to represent the planform of a regular ideal river and closely approximates the shape of real river meanders.[26] Transition entry and exit sections of a non-standard sinuosity were required for the main channel flow to enter and leave along the flume centreline. To enable the channel to be constructed within the constraints of the flume dimensions, the following relationship was necessary

$$L_m = 4\pi B \qquad (2)$$

20. The channel was designed to have a sinuosity of 1·34 where sinuosity is defined as the ratio of the curved meander channel length to the valley length. This gives a 60° angle between the main channel centreline and the centreline of the valley at the crossing point (the cross-over angle). A sinuosity of 1·34 correlates closely with the sinuosity range of 1·30–1·50 found in natural river channels formed in both non-cohesive sands and gravels.

21. The adopted planform incorporated two repeated meander units (see Fig. 1). This was the maximum number that could be accommodated. This array of repeated meanders, although different from conditions found in nature, improves the reliability of results and is similar to experimental set-ups used by others such as Willetts and Hardwick.[24]

22. The main channel (Fig. 2) has a trapezoidal cross-section with 45° sloping side walls and a top width of 1·6 m. A flat, or screeded sand bed, 0·2 m below the bankfull level, was formed along the length of the channel at the start of each experiment. The sand was closely graded with a d_{50} value of 0.835 mm (d_{15} = 0.646 mm; d_{85} = 1·052 mm).

23. Although the overall width of the FCF was 10 m, all tests were carried out with a reduced floodchannel width of 8 m by installing temporary longitudinal walls on the floodplain. These walls had a slope of 45°, giving the upper channel a trapezoidal cross-section. The floodplains had no crossfall normal to the valley direction and were used as the reference plane throughout the test programme. Post-construction surveys showed the longitudinal floodplain or valley slope to be $1{\cdot}8593 \times 10^{-3}$.

24. The water circuit of the flume was a closed loop in which clear water was recirculated. The flow entered the upstream channel end after passing over a knife-edged weir and through a stilling tank and left, at the other end, over a line of variable overshot weir plates, or tailgates, which controlled the flume conditions. Water was supplied by one, or more, variable capacity pumps, which drew water from a common sump at the downstream end of the facility. The discharge from each pump was

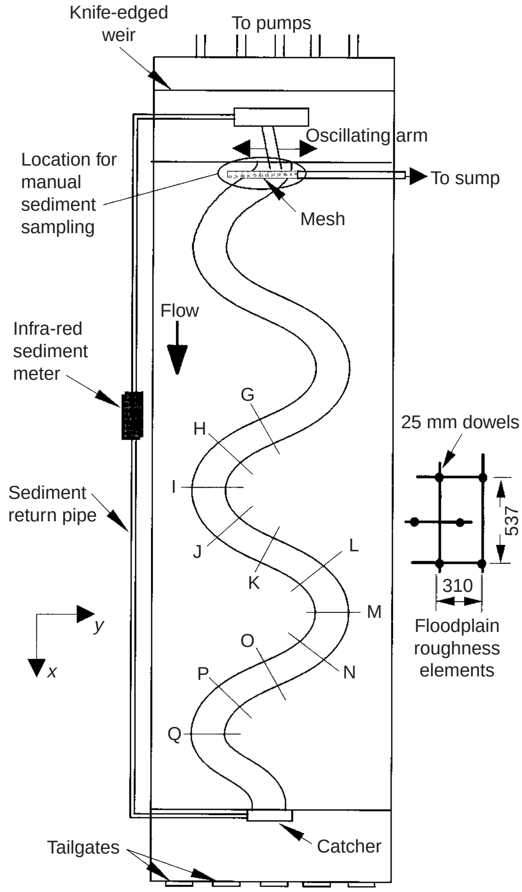

Fig. 1. Experimental arrangement at the FCF

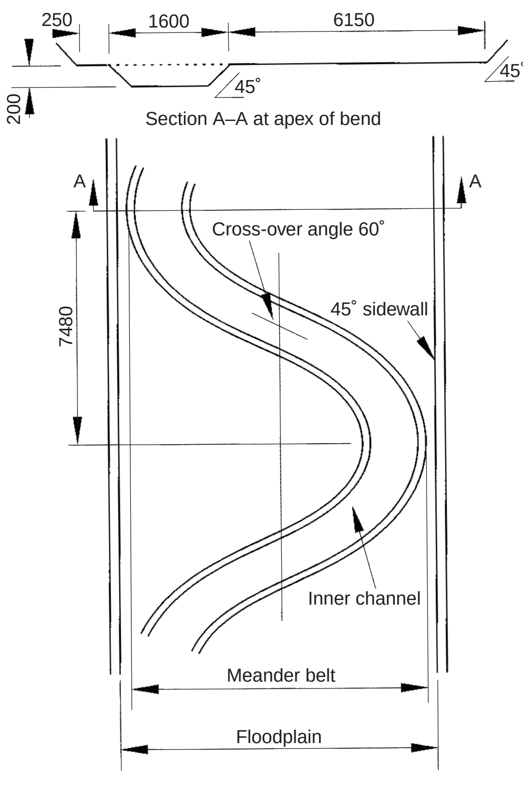

Fig. 2. Details of plan and cross-section geometry (dimensions in mm)

determined by an orifice plate fitted in each pump line. The head difference across each orifice plate was recorded by a water manometer. Transported bed-load was collected at the downstream lip of the main channel in a sediment catcher, and returned by a slurry pump to the upstream end of the main channel. Prior to joining the flow, the mixture travelled down an oscillating arm designed to spread the sediment over the full width of the main channel onto a 100 μm stainless-steel wire mesh, inclined at approximately 70° to the horizontal, which separated the sand and water. The sand was returned to the main flow and the water diverted to the sump. Recirculating the sediment eliminated the difficulties associated with single-pass feeding of large quantities of sediment for long periods of time.

25. The experimental programme consisted of one inbank, one bankfull and seven overbank experiments with the duration of each experimental run typically 70–80 h. Four of the overbank experiments used roughened floodplains to simulate the effects of vegetation. Roughening was achieved using a standard configuration of vertical rods, 25 mm in diameter, arranged in a regular rhomboidal pattern and held in place by frames (see Fig. 1). Roughness elements were surface-penetrating for all flow depths. Discharges of 0·175 m^3/s, 0·250 m^3/s, 0·350 m^3/s and 0·600 m^3/s gave overbank flow depths of 38–178 mm for roughened floodplains. Identical discharges, with the exception of 0·175 m^3/s, were used with smooth floodplains. Observations made during the test programme suggested that the 0·175 m^3/s overbank discharge for the smooth floodplain would give a very shallow overbank depth which would be difficult to measure. Measured floodplain depths ranged from 42 mm to 92 mm for the smooth floodplain experiments. A 0·050 m^3/s inbank flow and a 0·104 m^3/s bankfull flow were also measured.

26. The measured reach was located between chainages 27 m and 37 m from the upstream end of the flume. This corresponds to cross-sections I to O shown in Fig. 1. For all experiments, the data relating to water surface slopes, main channel and floodplain velocities, sediment transport and bed forms, were recorded. Water temperatures were also recorded.

27. Water surface slopes were determined by measuring surface levels relative to the floodplain normal to and centrally above the main channel direction at sections G to Q. Levels were measured using a manually-operated digital point gauge mounted on the instrument carriage. The carriage traversed the main channel using a system of rollers resting on a bridge, which moved along the flume on rails set in the horizontal plane. With the fluctuating water surface, the surface levels were recorded to an accuracy of ± 1.0 mm.

28. After running each experiment for approximately 15 h, five slope readings for a particular tailgate setting were taken over a period of time. A minimum of three tailgate settings, giving a range of slope values through the surveyed floodplain slope, were examined. Sufficient time was allowed for the channel to adjust to the new water surface slope brought about by the tailgate changes. Interpolation of this data yielded the tailgate setting giving normal depth and uniform flow along the channel. Because the free surface is not plane and parallel to the channel slope, as it is in the case of straight channels, uniform flow in a meandering channel is defined as occurring when longitudinal surface profiles relative to the floodplain are replicated from meander to meander.[24]

29. A rectangular grid of main channel velocities was measured at cross-sections I to O using a two-dimensional Sontek ultrasonic velocity probe which enabled longitudinal and transverse velocities to be recorded simultaneously. Velocities were recorded at each point for 30 s at a frequency of 25 Hz. Floodplain velocities were measured at cross-sections I, L, M and O at intervals of 0·5 m along a line normal to the valley direction passing through the intersections of the channel and floodplain centrelines. These velocities were recorded at 40% of the overbank depth. Floodplain velocities were sampled at a frequency of 25 Hz for a period of 60 s. The overbank velocities for the 0·175 m^3/s overbank rough and 0·250 m^3/s overbank smooth flows were recorded using a miniature propeller meter, as the overbank water depth was insufficient for the Sontek probe to function effectively.

30. The bed-load in the flume was measured automatically by a calibrated infrared sediment meter installed in the return pipe of the sediment recirculation system. Regular checks were made on the catcher to ensure that no storage of sediment was occurring. Additional, manual sediment sampling was undertaken using mesh-bottomed baskets at the point at the upstream end of the channel where the recirculated sediment would normally have entered the inner channel (see Fig. 1). An upstream sampling location was preferred because results from downstream sampling have, in the past, indicated that sediment baskets, when placed above the catcher, lower the value of the downstream water surface slope and the bed shear stress, resulting in underestimated sediment transport rates.

31. Following the completion of data collection for each experiment, the channel was slowly drained. Slow drainage eliminated the possibility of slump in the bedforms. Bedforms were measured in the drained channel using an automatic bed profiler normal to the local inner channel direction at cross-sections G to Q with

horizontal intervals of 25 mm. The bed profiler recorded to an accuracy of $\pm 2{\cdot}0$ mm in the horizontal plane and $\pm 1{\cdot}5$ mm in the vertical plane.

Experimental results

32. The experimental channel was used with nine measured flows. Fig. 3 shows the stage discharge curves obtained. As described in the previous section, discharges were measured using orifice plates fitted to the pump lines. The stage discharge curves shown in Fig. 3 are for an apex bend section. The stage datum was taken as the screeded bed level which is 200 mm below bankfull for the main channel. The stage was measured at the water surface above the main channel section and midway across it.

33. The stage discharge curves diverge when flow goes overbank, showing higher discharges for smooth floodplain flow. A smaller range of overbank flow depths is present for smooth floodplain flows. The maximum ratio for the range of discharges selected is: maximum discharge: bankfull discharge = 6:1. The range of relative depths for overbank flow with the rough floodplain is $0 \leqslant Y_r \leqslant 0{\cdot}470$ and with the smooth floodplain $0 \leqslant Y_r \leqslant 0{\cdot}314$.

34. In order to find overbank stage discharge relationships of the form $Q = K\,d^n$, best fit regression lines were fitted to the overbank stage discharge points. Fig. 4 shows the two fitted lines with the stage discharge data points; both axes of Fig. 4 are logarithmic scales. It can be seen that despite the small number of points, the scatter around the fitted lines is quite small for the data range.

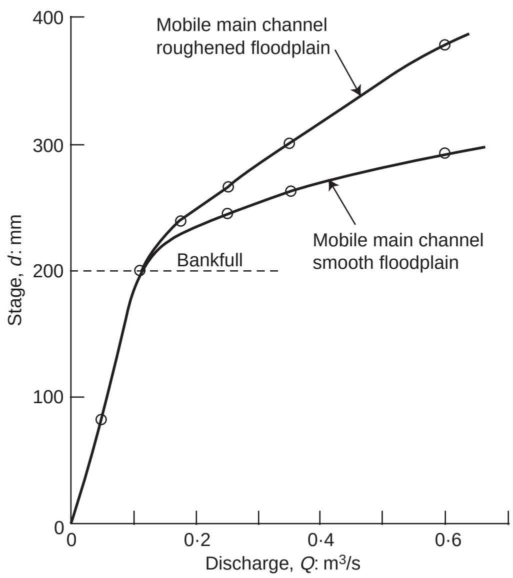

Fig. 3. Stage–discharge curves—inbank and overbank flow

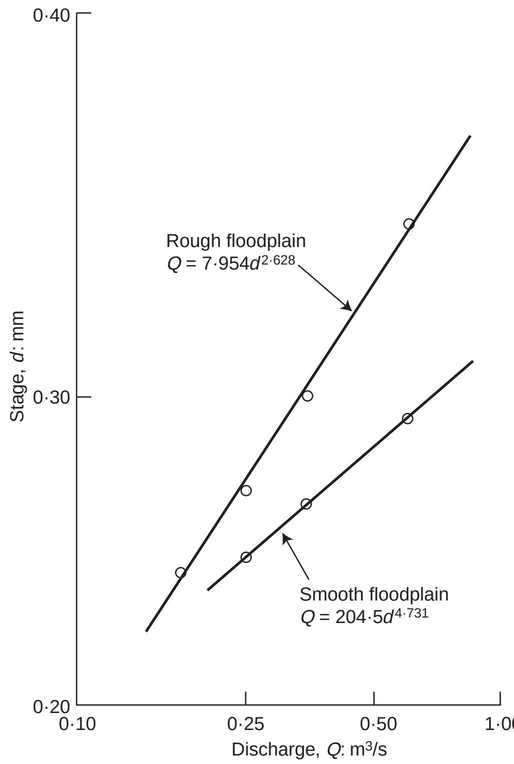

Fig. 4. Stage–discharge relationships—overbank flow

35. The overbank stage discharge relationships obtained from the regression analysis are

$$Q = 7{\cdot}954\,d^{2{\cdot}628} \quad \text{rough floodplains} \tag{3}$$
$$Q = 204{\cdot}5\,d^{4{\cdot}731} \quad \text{smooth floodplains} \tag{4}$$

or in non-dimensional form

$$Q_r = 12{\cdot}832 Y_r^{1{\cdot}187} \quad \text{rough floodplains} \tag{5}$$
$$Q_r = 33{\cdot}471 Y_r^{1{\cdot}549} \quad \text{smooth floodplains} \tag{6}$$

where $Q_r = Q/Q$ bankfull.

36. Figure 5(a) shows depth-averaged floodplain velocity components for an apex cross-section, for a discharge of $0{\cdot}350\,m^3/s$. It can be seen that the main longitudinal velocity component, $\boldsymbol{V}_x$, is higher for the smooth floodplain than the rough floodplain. There is an increase in velocity component, $\boldsymbol{V}_x$, over the main channel for the rough floodplain case, giving higher velocities across the top of the main channel than on the floodplain for this flow of $0{\cdot}350\,m^3/s$ corresponding to a relative depth of $Y_r = 0{\cdot}333$. Also shown on Fig. 5(a) for the apex section are the transverse velocity components $\boldsymbol{V}_y$. Both the smooth floodplain and the rough floodplain show a reversal of sign of the $\boldsymbol{V}_y$ component across the main channel, which indicates water flowing towards the centre of the main channel from each bank. The magnitude of this circulation into the main channel from the floodplains is much smaller for the smooth floodplain case than for the rough floodplain. The rough floodplain causes more water to move to the main channel at the bend

apex. Transverse velocity components, $\boldsymbol{V}_{\mathrm{y}}$, for the smooth floodplain case are small compared with the longitudinal components, $\boldsymbol{V}_{\mathrm{x}}$, and for the rough floodplain are approximately 30% of the longitudinal components.

37. Depth-averaged velocity profiles at a cross-over are shown in Fig. 5(b). The rough floodplain longitudinal velocities, $\boldsymbol{V}_{\mathrm{x}}$, are lower than those for the smooth floodplain but follow the same trend. Velocities on the left floodplain, with an apex upstream, are higher than those on the right floodplain. The transverse velocity component, $\boldsymbol{V}_{\mathrm{y}}$, shows a reversal in sign on the left floodplain for the section which is downstream of an apex. The reversal is stronger for the smooth floodplain than the rough floodplain. Over the main channel the rough floodplain transverse velocity components, $\boldsymbol{V}_{\mathrm{y}}$, are of the same magnitude as the longitudinal components, indicating that the main direction of flow is approximately in the main channel direction. For the smooth floodplain case the longitudinal average velocity, $\boldsymbol{V}_{\mathrm{x}}$, is approximately four times the transverse average velocity, $\boldsymbol{V}_{\mathrm{y}}$, indicating a mean flow direction approximately 15° to the longitudinal direction.

38. Figure 6 shows the average velocities for the main channel and the floodplain for overbank flows. Floodplain average velocities are generally higher than main channel average velocities and smooth floodplain velocities are higher than rough floodplain velocities for the range of relative depths $Y_{\mathrm{r}} > 0{\cdot}150$. Because of the smaller flow resistance of the smooth floodplain, higher discharges and velocities are found than for the rough floodplain at any particular overbank flow depth.

39. Using the bed and velocity profiles for the main channel below bankfull level during overbank flows, it was possible to calculate proportions of flow in the inner channel and the floodplain. The 'floodplain' is taken to comprise all flow above the inner channel bankfull level. Fig. 7 shows the proportions of flow. Floodplain flows for the smooth case at any depth are greater than the rough floodplain flow, as shown on the stage discharge curves in Fig. 1. Fig. 7 shows that the proportion of flow on the floodplain is larger for smooth floodplain flows up to a relative depth of $Y_{\mathrm{r}} = 0{\cdot}300$. The rough floodplain case, therefore, has more flow in the main channel, reflecting the greater flow resistance of the floodplain.

40. Using the longitudinal valley slope and the section geometry for each flow case, it was possible to determine a 'single channel' value of Manning's n at the apex cross-section. Fig. 8 shows the variation of single-channel Manning's n with depth. The inbank values increase to $n = 0{\cdot}0206$ at bankfull. After bankfull, the smooth floodplain values decrease slightly from the bankfull value and tend to a constant value of $n = 0{\cdot}0166$. Overbank flows with a rough floodplain show increasing values of Manning's n with increasing depths. The increase is from the bankfull value of $n = 0{\cdot}206$ to $n = 0{\cdot}0435$ at $Y_{\mathrm{r}} = 0{\cdot}470$. The roughening of the floodplain with surface-penetrating rod elements was expected to produce increasing flow resistance with increasing depth.

41. A single-channel value of the Darcy–Weisbach friction factor λ was also calculated for the apex section using the valley slope. The variation of friction factor with relative depth is shown in Fig. 9. The inbank values increase

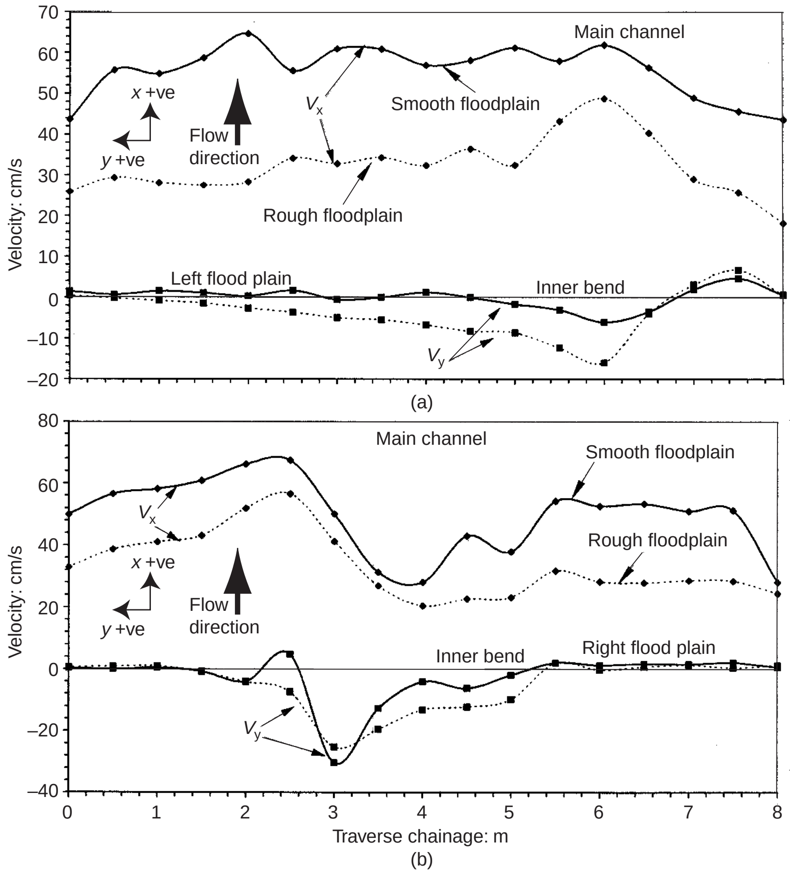

Fig. 5. Floodplain depth-average velocity components for: (a) apex I; and (b) cross-over O (discharge = $0{\cdot}350\,m^3/s$)

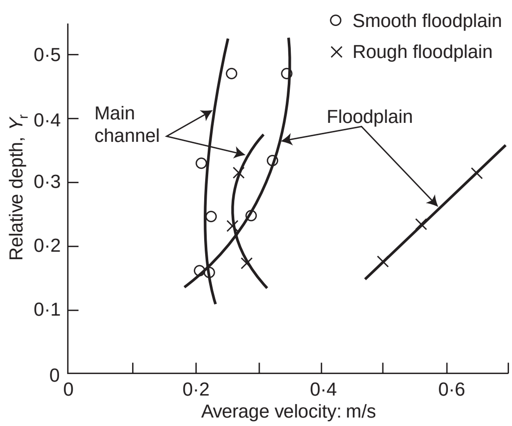

Fig. 6. Average velocities in main channel and floodplain

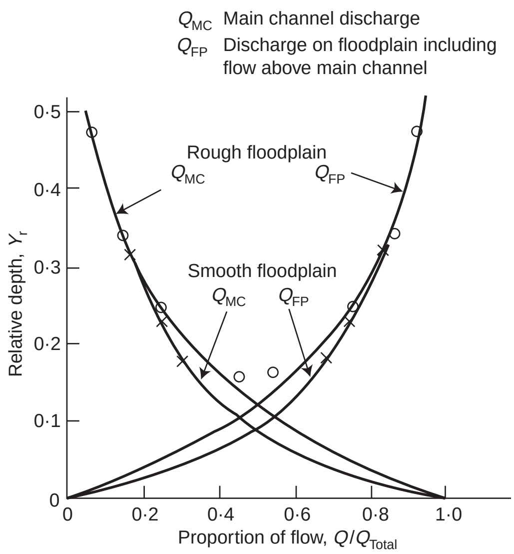

Fig. 7. Proportions of flow in main channel and floodplain

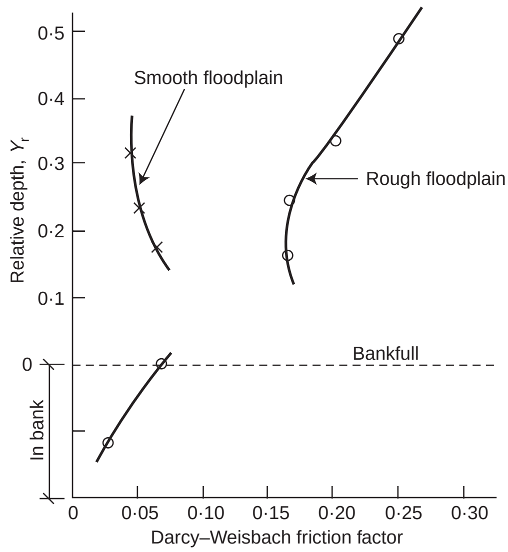

Fig. 9. Variation of single-channel friction factor with depth

to the bankfull values of $\lambda = 0{\cdot}067$. The overbank value of λ for the smooth floodplain decreases from the bankfull value and tends to a constant value of approximately 0·035. The overbank values of λ for the rough floodplain show an increase with increasing depth of flow. Again, the increasing roughness with the surface-penetrating rods leads to increasing λ with increasing depth. Rough floodplain values of λ are three to six times the value for smooth floodplains.

42. Considering the flows in the main channel below bankfull and in the floodplains separately, it is possible to calculate separate Manning's n values for the main channel and the floodplain. For this calculation the horizontal interface between the main channel and the floodplain flow at bankfull level is neglected for the wetted perimeters of the main channel and the floodplain. Fig. 10 shows the variations of the separate Manning's n values. It can be seen that main channel values of Manning's n decrease with increasing relative depth and the main channel Manning's n values for the smooth floodplain case are smaller than those for the rough floodplain. Smooth floodplain values of Manning's n do not vary significantly in the range $0{\cdot}150 \leqslant Y_r \leqslant 0{\cdot}350$ but rough floodplain values of Manning's n show a large variation in the range $0{\cdot}150 \leqslant Y_r \leqslant 0{\cdot}470$ which is associated with the surface-penetrating rod roughness elements used on the floodplain.

43. Main channel bed profiles for bend apex and cross-over sections are shown in Fig. 11. Profiles are shown for bankfull, $0{\cdot}104\,m^3/s$, and the largest experimental flow, $0{\cdot}600\,m^3/s$, for a smooth and a rough floodplain case. The apex cross-section for bankfull flow shows the bed much deeper on the outside of the bend,

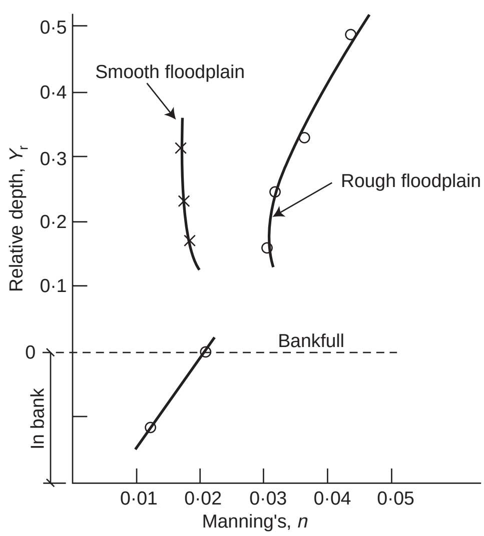

Fig. 8. Variation of single-channel Manning's n *with depth*

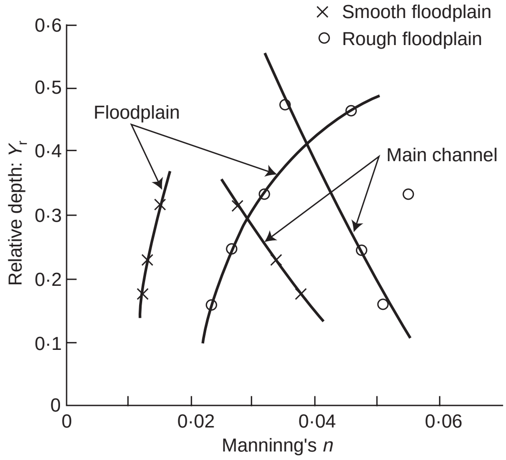

Fig. 10. Manning's n *for main channel and floodplain*

indicating much higher velocities there compared with the inside of the bend where deposition has taken place. As previously described, following the completion of flow data collection, the channel was slowly drained to eliminate slumping of the bedforms. Figs 12 and 13 show photographs of the bedforms for smooth and rough floodplains for flow of 0·600 m^3/s. It can be seen that the typical bedforms are long dunes repeating through the length of the main channel. The smooth floodplain bed profile for the apex with the flow of 0·600 m^3/s is shallower than that for the rough floodplain, suggesting higher main channel velocities for the rough floodplain case.

44. The bed profiles for the cross-over section show that the rough floodplain case produces a higher bed than that for the smooth floodplain with a more regular shape.

45. It should be noted, however, that the bed profiles shown may not correspond to the same positions along the dunes and only limited comparisons between bed profiles at particular cross-sections can be made.

Conclusions

46. The conclusions of this study can be summarized as follows.

(*a*) A programme of experimental work on meandering, mobile bed compound channels using the UK FCF has been described. This experimental work forms part of a long-term programme using the UK FCF.

(*b*) Using a literature review, the research programme has been set in the wider context of compound channel research.

(*c*) Equations describing stage–discharge relationships for smooth and roughened floodplains have been derived. Floodplain roughness progressively reduces discharge capacity by up to 40% at large depth.

(*d*) The transverse velocity, $\boldsymbol{V}_y$, for overbank flow at the meandering main channel bend apex shows evidence of plunging flow taking water into the main channel at the bend apex.

(*e*) For overbank flow with relative depth $Y_r > 0{\cdot}2$, valley direction floodplain average flow velocity is greater than meandering main channel average flow velocity.

(*f*) Floodplain roughness progressively increased single-channel values of Manning's n and Darcy–Weisbach λ by up to 100% and 300% respectively at large depth.

(*g*) The mobile bed main channel Manning's n value was generally greater than floodplain Manning's n for both the rough and smooth cases. At higher overbank flow relative depths, $Y_r > 0{\cdot}400$, the main channel and floodplain Manning's n values became similar.

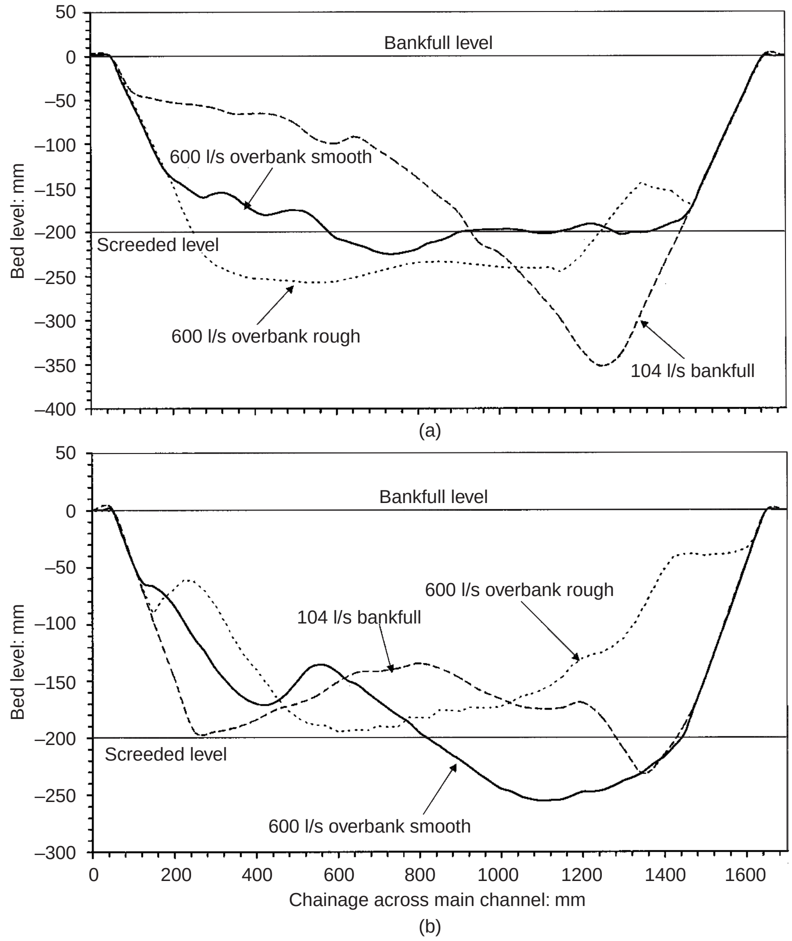

Fig. 11. Main channel bed profiles for: (a) apex I; and (b) cross-over O

(*h*) The principal bedforms observed in the main channel with the smooth floodplains were repeating dunes of amplitude 40–80 mm with a crest-to-crest distance in the range 450–700 mm. Main channel bedforms for roughened floodplains were more variable.

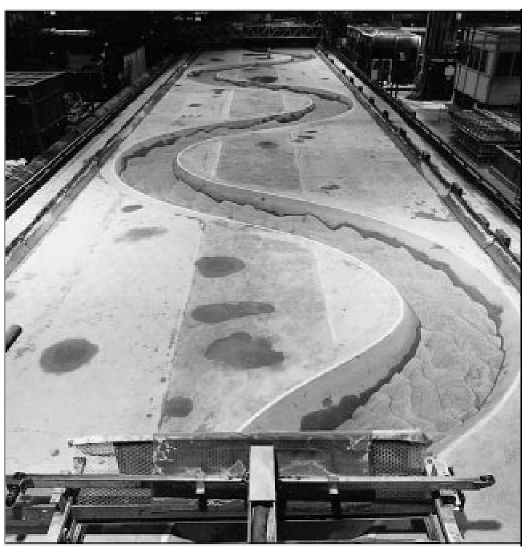

Fig. 12. Main channel bedforms—smooth floodplains—for flow of 0·600 m^3/s

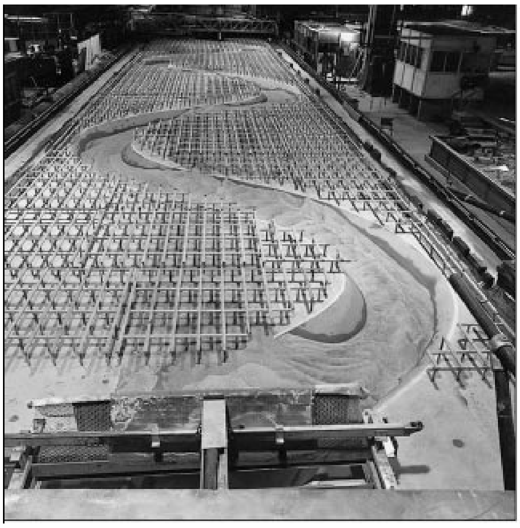

Fig. 13. Main channel bedforms—roughened floodplains—for flow of 0·600 m³/s

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