Regime theory and the stability of straight channels with bankfull and overbank flow

La théorie de régime et la stabilité des chenaux droits sous les conditions des écoulements à ras bord et débordés

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ABSTRACT
Experiments have been carried out at a large laboratory scale to test a rational regime theory and to study the development of regime channel morphology for straight loose-boundary channels (bed and banks) in fixed flood plains for a range of flow conditions. Results are presented for straight channels which have been developed with bankfull flows and then subjected to overbank flows, and include friction and sediment transport data. These indicate reasonable theoretical agreement with the friction data but the sediment transport rate is underestimated. Stability of the main channel was assessed in response to bedforms, bank erosion and hydraulic friction and sediment transport. For overbank flows, rates of bank erosion have been measured. These measurements constitute unique overbank widening data for the main channel.

RÉSUMÉ
Des expériences ont été effectuées à grande échelle en laboratoire pour tester une théorie rationnelle de régime, et pour étudier, sur une gamme de conditions d'écoulement, le développement de la morphologie des canaux rectilignes aux limites instables (lit et rives) dans des plaines d'inondations fixes. Les résultats sont présentés pour les canaux droits qui se sont développés avec des écoulements à ras bord puis à débordement ; ils incluent les données de frottement et de transport solide. Celles-là indiquent un accord raisonnable avec les données de frottement théoriques, mais le taux de transport solide est sous-estimé. La stabilité du canal principal a été évaluée en fonction des formes de lit, de l'érosion des berges, du frottement et du transport solide. Pour les écoulements avec débordement, les taux d'érosion des berges ont été mesurés. Ces mesures constituent des données uniques pour l'élargissement, par débordement, du canal principal.

1. Introduction

Despite decades of research, the task of designing stable alluvial channels, or stabilising natural rivers, is only partly supported by an adequate theory. Currently the so-called extremal or rational methods appear most promising. These propose that an alluvial channel evolves to a regime geometry as one of its energy-related properties tends to acquire its extreme value (e.g., Yalin, p. ix [25]; Davies and Sutherland [7]). Three equations are solved simultaneously, usually for flow resistance, sediment transport and minimization or maximization of the energy-related property. The third equation has, for example, been considered to be the maximisation of sediment transport or the minimisation of stream power, which have been shown to be equivalent. For a given granular material and fluid, and knowing water and sediment discharge, the channel width, depth and slope can then be determined. Deficiencies in the rational methods include the semi-empirical nature of all practical flow resistance and sediment transport equations, a certain subjectivity in the choice of the energy-related property and the need to simplify the natural complexity of the river environment, especially unsteady flow conditions. Most regime calculations use the concept of a single channel-forming (or dominant) discharge (often evaluated as the bankfull discharge), assuming that, over a period of time, this single discharge represents the cumulative effect of the actual time-varying discharge. On this basis, progress has been made in predicting the regime conditions for straight, single-stage, mobile bed channels (e.g., White *et al.* [23], Valentine [18]; Babayean-Koopaei and Valentine [4]). However, no explicit account is taken of floodplain interaction with the main channel. There is a need, therefore, to develop prediction techniques which can be applied to two-stage, loose-boundary channel design, allowing for the effects of overbank flows.

The difficulties of taking measurements at the field scale and the limited relevance of most, typically rather small-scale, laboratory experiments means that there is a lack of data on overbank flows in mobile channels. However, through its use of the unique 10 m wide Flood Channel Facility (FCF) at HR Wallingford, UK, this study is able to report a significant advance in data collection. Specifically, work was carried out to collect experimental data relevant to the regime behaviour of a straight, loose boundary (bed and banks) channel in a floodplain, to investigate the stability of the channel for overbank and bankfull discharges and to assess the performance of a rational regime method in predicting a stable channel geometry. The White, Bettess and Paris [22]) theory (hereafter referred to as the WBP theory) was selected on the grounds of previous familiarity with the method, gained in flume studies (Valentine and Shakir [19]; Babaeyan-Koopaei and Valentine [4,5]). The method assumes maximisation of sediment load and uses the flow resistance formula of White *et al.* [22] and the sediment transport formulae of Ackers and White [2] and Ackers [1]. Important features of the study include sediment transport and channel cross-section response to overbank flow, inclusion of mobile banks as well as mobile bed and more realistic width/depth ratios than those of many previous laboratory experiments (up to 40 at bankfull flow).

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2. Experimental design

As the aim of the experiments was to provide data for testing a rational regime method, the channel had to conform as closely as possible to the characteristics of an ideal regime channel. In particular, the sediment load was required to be unchanging in every aspect throughout time and space. There should, therefore, be no overall aggradation or degradation of any cross-section along the channel. Recognizing, though, the difficulty of achieving true boundary steadiness in free-form laboratory channels, the less severe and more easily achievable constraint of boundary and flow uniformity in the measurement reach of the flume formed the minimum requirement for the experimental design. On this basis, measurements of sediment transport at the end of the flume would still be relevant for the entire experimental reach.

In the experiments the channel slope, discharge and sediment properties were the controlled independent variables, kept as uniform and as steady as possible. Sediment in transport was recirculated at a rate assumed to be uniform as long as the channel width, depth and bank profile were demonstrably uniform, these being the dependent variables, free to vary over time. An important task in the data analysis was to demonstrate the degree of uniformity and steadiness in the experimental conditions.

The starting point for the experiments was the establishment of an equilibrium or near equilibrium channel with bankfull flow. In order to achieve this, the WPB method was first used to calculate the initial channel dimensions, given particle size, bed slope and discharge. A small allowance for the angle of repose of loose sediment in the banks was made when screeding the initial geometry, producing a trapezoidal channel cross-section of equal area and width to the WPB prediction.

Experience of operating similar experiments at small scales (Valentine and Shakir, [19]; Babaeyan-Koopaei and Valentine [5]) has shown that equilibrium straight channels can be achieved in the laboratory but that they are consistently wider and shallower than predicted (for a limited particle size and flow range), albeit with a similar cross-sectional area. Preliminary tests with the FCF produced the same result: initial screeds with higher width/depth ratios than predicted by the WPB method gave greater bank stability, at least in the range of bankfull discharges investigated. For example, with a discharge of 25 l s^{-1} and slope range of 1.02 x 10^{-3} to 1.83 x 10^{-3} m m^{-1}, the predicted straight stable channel was 0.64 m wide and 94 mm deep. However, from these experiments, the most stable channel under these conditions and carrying a similar sediment load, was found to be a little over 1.6 m wide and 41 mm deep. The wider cross-sections were therefore subsequently used as the initial conditions for the main sequence of experiments.

The reported experiments involved straight channels only but with bankfull and overbank flows.

3. Data collection

The data were collected during 1995 and 1996 according to equipment availability.

Experimental conditions

The Flood Channel Facility (FCF) is a 10 m wide by 56 m long fixed slope flume designed for study of the interaction between floodplain and main channel flows. A full description may be found in Knight and Sellin [11], Sellin *et al* [15]) and Knight *et al* [12]. For all the experiments the floodplain slope was 1.84 x 10^{-3} m m^{-1} and the sediment consisted of a near-uniform, sub-rounded silica sand of $D_{35} = 0.74$ mm, $D_{50} = 0.84$ mm, $D_{90} = 1.08$ mm and $\sigma_D \approx 1.3$, where D_n is the size for which n% of the material is finer and $\sigma_D = D_{90}/D_{50}$. Water temperature varied between 8 and 14°C, giving a kinematic viscosity of 1.27 ± 0.11 x 10^{-6} m^{2}s^{-1}.

The experimental channels were mostly screeded to empirically derived dimensions for bankfull flows of 25 and 45 l s^{-1} (1.6 m wide and 41 and 70 mm deep respectively). These flows were chosen as a result of initial test runs and were found to combine good bank stability with significant overbank depth. A few were screeded for 10 l s^{-1} to provide a connection with the maximum discharge in previously reported experiments at the University of Newcastle upon Tyne (Valentine and Shakir, [19]; Babaeyan-Koopaei and Valentine, [4]). Screeding was performed with a wooden template in the centre of a 2 m wide region of mobile sediment, with the level of the banks as close to that of the floodplain surface as possible.

The floodplains were 3 m wide on both sides of the 2 m wide mobile region, moulded with a sand and cement mortar. Additional floodplain roughness was provided by regularly spaced wooden dowels of diameter 25 mm, regularly spaced with a density of 12 per square metre. Total compound discharges up to 140 l s^{-1} were used, giving floodplain depths up to around 40 mm.

Additional data for near bankfull discharges were collected with the 2.5 m wide, 18 m long tilting flume, also at HR Wallingford. The same sediment was used and eight experiments were carried out at slopes between half and twice that of the FCF. Initial channel widths, which were less than 1.06 m, were again based on the WPB method. Bankfull discharges varied from 4 to 51 l s^{-1}.

Measurements

Total water discharge was measured by orifice plates in the flume supply pipelines. Water surface elevation and slope were measured with electronic point gauges mounted on levelled instrument carriages, in both flumes. Instrument accuracy, combined with the large ratios of flume length to flow depth (up to 1000), ensured good quality slope data even when bedforms were observed.

Sediment transport was measured manually at the discharge end of the sediment recirculation system. In the later experiments, the manual technique was supplemented by an infra-red turbidity meter inserted in the sediment recirculation pipeline. Transport rates proved reasonably steady and repeatable in spite of bedform development.

Channel widths and depths were measured manually during the experiments and in more detail by the HR Wallingford designed, "touch sensitive", automatic bed profiler at the end of experiments. In some cases the initial channel was also profiled to enable aggradation/degradation to be measured accurately.

Experimental procedure

In the relevant experiments overbank flow was not started until after a period of bankfull discharge. This allowed a near-regime bankfull condition to be established and extra data for bankfull conditions to be collected. Some of the experiments were also repeated as a check on consistency.

The bankfull experiments were of sufficient duration and had a smooth enough water surface to permit good control of water surface slope and allow the development of uniformity in behaviour along the entire length of the flume. For the overbank experiments, preparation time was longer and water surface slope data were difficult to collect, especially as run times were relatively short. It was not possible to dedicate the time to a series of tests to obtain normal depth for each flow and rapid judgement and adjustment of flow and downstream control had to be relied upon. However, while some overbank flows had noticeable backwater effects, many had a test section slope close to that of the preceding bankfull flow and produced little or no measurable overall deposition or erosion at the downstream end of the flume.

Calculation of hydraulic parameters and errors

To exclude the effect of bed features from the calculation of hydraulic radius, the channels were assumed to have simple trapezoidal cross-sections. This was a good approximation for the bankfull experiments and the average flow cross-section could be calculated from the profiler data collected at the end of the experiment and from the water surface measurements during the experiment. The overbank flows, though, tended to produce more dish-shaped channels with gentler side slopes and the trapezoid proved a less satisfactory fit.

As a basis for comparison of bankfull and overbank experiments and for the calculation of flow resistance and sediment transport, hydraulic radius values were calculated for the main channel only. For the bankfull flows the wetted perimeter and flow cross-sectional area were determined for the best-fit trapezoid. For the overbank flows, the cross-sectional area was determined assuming a vertical interface with the floodplain flow. However, the wetted perimeter was not extended to the (short) vertical water/water interface and no attempt was made to quantify the interaction of main channel and floodplain flows. As the channels commonly had width/depth ratios of 20 or more, though, the exact detail of the bank geometry had little effect on the calculations.

Data summary

Table 1 summarizes the experiments, which are divided into three main groups. The first concerns bankfull experiments for a range of discharges and slopes in the FCF and tilting flume, most of which lasted for a day or more. These indicate the long term behaviour and stability of the initially straight channels and form the basis for choosing the principal test bankfull discharges of 25 and 45 l s^{-1}. This choice represented the range of stable bankfull discharges constrained by the FCF slope and the bed sediment. The second group are the bankfull experiments carried out with these discharges, lasting from 2 to 9 hours. The group is split into two series corresponding to the two periods in 1995 and 1996 when the work was carried out. The final group refers to the FCF overbank experiments: these are nearly all linked to one of the bankfull experiments, which formed the initial conditions for the overbank study. As well as indicating the basic flow parameters, Table 1 shows the duration of each experiment and the final channel morphology and bedform.

4. Stability analysis

Before using the data to assess the WPB regime theory, it was necessary first to demonstrate that the experimental conditions corresponded to the ideals of uniformity and steadiness outlined earlier.

It may be concluded that the channels exhibited quasi-steadiness, although none were characterized by a truly steady boundary geometry. All the channels widened gradually or changed their planform, to alternating bars and meanders. However, for the inbank flows, the changes occurred very slowly, over tens of hours or days: typical rates of widening were only 1-2% per hour. Figure 1 shows the variation in top width for channels of bankfull discharge 25 and 45 l s^{-1} for several imposed flows and durations of flow. Excellent repeatability is evident and the rate of change measured in experiments with short durations of bankfull flow was maintained in separate experiments lasting for longer periods. The quasi-steady nature of this increase is evident in the context of the much greater rates of width change which accompany the increase in discharge from bankfull to overbank for the two experiments so executed with each design channel.

It may be noted that the discharges for which stable, straight, free-form laboratory channels in coarse sand have been reported elsewhere are restricted to less than 10 l s^{-1} (e.g., Wolman and Brush [24]; Ikeda [8]; Shakir [16]; Babaeyan-Koopaei and Valentine [5]; Ayyoubzadeh, [3]). The FCF experiments therefore considerably expand the range of data for quasi-equilibrium channels.

To ensure that data were collected for straight free-form channels in the FCF, the experiments were restricted to the period after starting when the form of the banks and the bedform flow resistance had been established but no tendency towards alternating bar formation could be observed. In spite of the slight boundary unsteadiness, these channels remained strikingly uniform for several hours or more, even with overbank flow and at the different slopes and discharges of the tilting flume. Figure 2 shows three final cross-sections for experiments with the 25 l s^{-1} bankfull discharge channel, for the same initial screed. Noting the vertical exaggeration of the scales and the presence of dunes on the bed, the difference between the two bankfull cases is insignificant, despite the different experiment durations. The trapezoidal mean cross-section is also evident. The overbank case is characterized by a slightly larger width and less steep sides, corresponding to its greater instability. Nevertheless the divergence from the

Table 1. Straight loose-boundary, bankfull and overbank channels. List of experiments.

Date	**Q**	**screed dimensions, m**		**Mean h**	**Slope**	**Duration**	**Final morphology**
	l/s	**B (top width)**	**h (depth)**	**mm**	***1000**	**Hours:min**	
FCF BANKFULL RUNS FOR LONG TERM CHANNEL BEHAVIOUR							
210295	10	1.31	0.030	28	2.2	42:00	meander
060295	14	0.75	0.060	43	2.1	18:00	alt. bars
010395	19	1.65	0.038	36	1.7	9:30	straight/dunes
130295	19	0.68	0.097	51	2.2	20:00	ab/dunes
160295	18	continuation 130295 (~1.4*0.04m)		37	1.9	54:00 total	alt. bars
250195	32	1.00	0.119	78	1.9	49:00	ab/dunes/meander
310195	40	1.00	0.119	87	1.9	27:00	alt. bars/dunes
080295	52	1.00	0.119	77	1.9	25:00	alt. bars/dunes
240595	23	1.61	0.041	40	1.8	24:00	alt. bars
151295	11	1.31	0.030	28	1.8	64:00	meander
TILTING FLUME BANKFULL RUNS FOR LONG TERM CHANNEL BEHAVIOUR							
160496	4	0.30	0.07	33	1.9	24:00	steady? straight
180496	5	0.30	0.07	30	4.0	24:00	meander
190496	4	0.30	0.07	30	1.6	72:00	steady? straight
230496	24	0.91	0.08	70	1.1	24:00	straight/dunes
250496	25	0.91	0.08	57	1.9	26:45	alt. bars/dunes
290496	29	0.91	0.08	48	3.2	5:30	alt. bars/dunes
020596	35	1.06	0.119	95	1.1	44:05	alt. bars/dunes
010596	51	1.06	0.119	68	3.6	2:00	alt. bars/dunes
1st SERIES FCF UNIFORM GEOMETRY BANKFULL RUNS							
050695	25	1.61	0.041	45	1.7	4:00	straight/dunes
300695	25	1.61	0.041	45	1.8	8:00	straight/dunes
010695	25	1.61	0.041	45	1.8	4:00	straight/dunes
070695	25	1.61	0.041	46	1.8	4:00	straight/dunes
040595	41	1.61	0.070	63	1.8	9:00	straight/dunes
190595	45	1.61	0.070	68	1.7	2:00	straight/dunes
160595	45	1.61	0.070	69	1.8	2:00	straight/dunes
180595	45	1.61	0.070	70	1.8	2:00	straight/dunes
110595	45	1.61	0.070	68	1.8	7:30	straight/dunes
2nd SERIES UNIFORM GEOMETRY BANKFULL FCF RUNS							
210196	25	1.61	0.041	45	1.9	7:00	straight/dunes
190296	45	1.61	0.070	69	1.9	7:00	straight/dunes
170196	25	1.61	0.041	44	1.8	4:00	straight/dunes
100196	25	1.61	0.041	44	2.0	4:00	straight/dunes
060296	45	1.61	0.070	69	2.0	2:00	straight/dunes
190296	45	1.61	0.070	69	2.0	7:30	straight/dunes
090296	45	1.61	0.070	70	1.8	2:40	straight/dunes
FCF UNIFORM GEOMETRY OVERBANK RUNS							
050695	47	32	12	58	1.7	4:00	straight/dunes
010695	62	37	18	62	1.8	4:00	straight/dunes
170196	81	44	26	77	1.7	3:00	straight/dunes
090296	95	55	26	98	1.8	1:20	straight/dunes
180595	84	59	18	89	1.8	1:30	straight/dunes
160595	105	65	27	108	1.7	1:00	straight/dunes
150296	133	67	40	120	1.5	0:45	straight/dunes

bankfull sections is small.

It was clear at an early stage that the experiments could not completely replicate the ideal uniformity and steadiness. However, they were characterized by a slow rate of widening, the maintenance of a uniform trapezoidal cross-section and straight planform and, additionally, much lower sediment mobility at the banks than in the bed region. Good repeatability of planform and width over time were also demonstrated. These characteristics are a notable experimental accomplishment. They provide a close approximation to the assumptions in the WBP method and a sufficient description of regime channels for the experimental data to be used to investigate rational regime theory and to assess the effects of overbank flow.

5. Experimental test of rational regime theory

The principal test of a rational regime theory concerns its prediction of stability at the extreme value of the relevant energy-related property. Before applying this test, though, it is necessary to examine the performance of the flow resistance and sediment transport equations which support the theory. Only if these equations apply satisfactorily is the test of the extremal hypothesis unambiguous.

Flow resistance

Manning's resistance coefficient, n, was calculated for the main channel flow for both bankfull and overbank flow experiments,

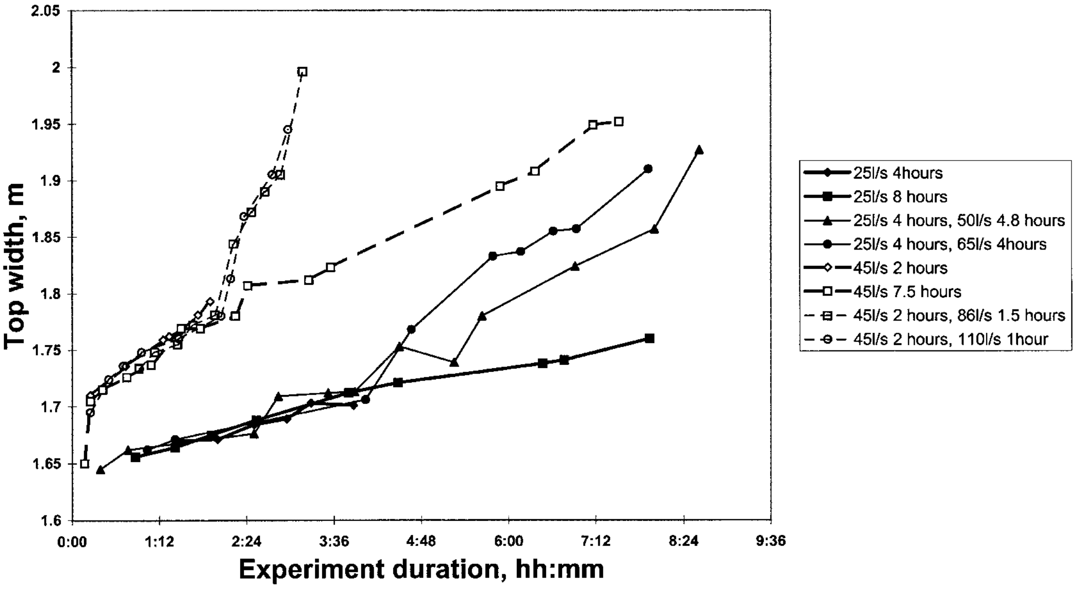

Fig. 1. Variation in top width for channels of bankfull discharge 25 and 45 l/s.

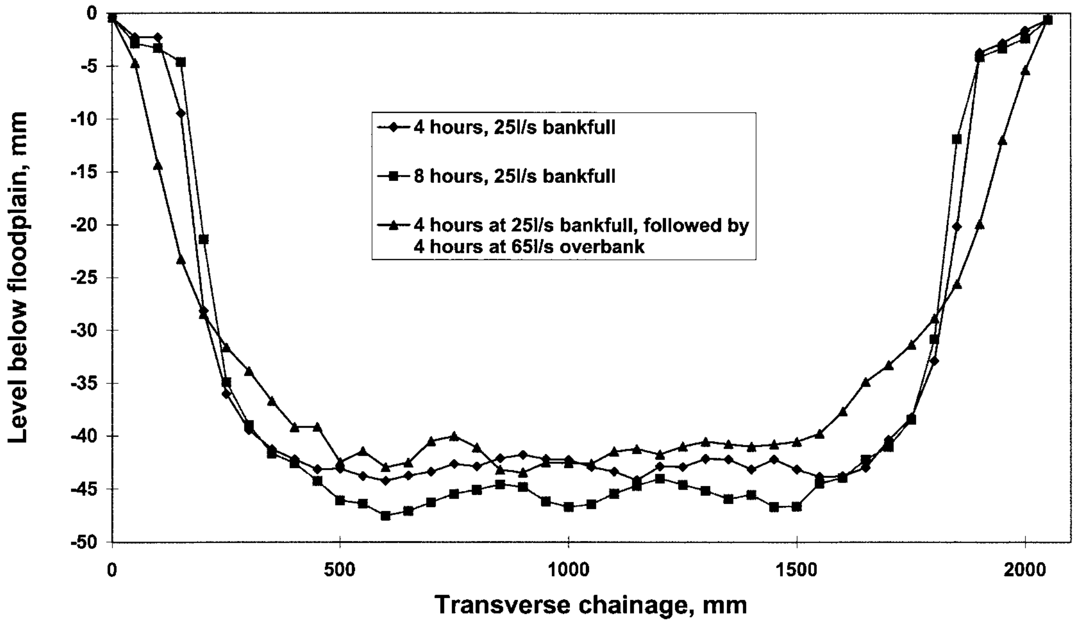

Fig. 2. Three final cross-sections for experiments with the 25l/s bankfull channel with the same initial screed.

with the necessary channel parameters calculated as explained earlier. To test for the effect of unsteadiness in channel width, the calculations were carried out both for the onset of what were believed to be uniform (steady) conditions and for the end of the experiment.

In the case of the main FCF experiments (with the 25 and 45 l s^{-1} channels), resistance was essentially steady within experimental error after the first 40-60 minutes of flow (characterised by bedform development), in experiments of typically several hours duration.

Figure 3 plots the resistance coefficient (range about 0.011-0.024) against hydraulic radius (range mainly 25-90 mm) using the free form channel data and a limited set of data from the FCF experiments with rigid bank bankfull and below bankfull flows (marked B/U) conducted by Knight and Brown [10] and Myers and Cassells [13]. These latter experiments were similarly two-dimensional and used the same sediment as the free-form channel experiments but had several tens of hours to reach equilibrium. For all the data points slope is within 10% of the FCF slope (1.84 x 10^{-3} m m^{-1}). Data from the free-form and rigid bank channels are indistinguishable from each other, indicating that the effect of the banks on the behaviour of the bed was relatively unimportant. Similarly, the data for the bankfull and overbank flow experiments are consistent (within experimental error), indicating the relative unimportance of the effect of floodplain and main channel flow interaction.

The plotted data show resistance coefficient values to increase as hydraulic radius increases, suggestive of an increasing bedform effect and consistent with observations of two-dimensional dunes. Figure 3 compares the observed pattern with the predictions of the

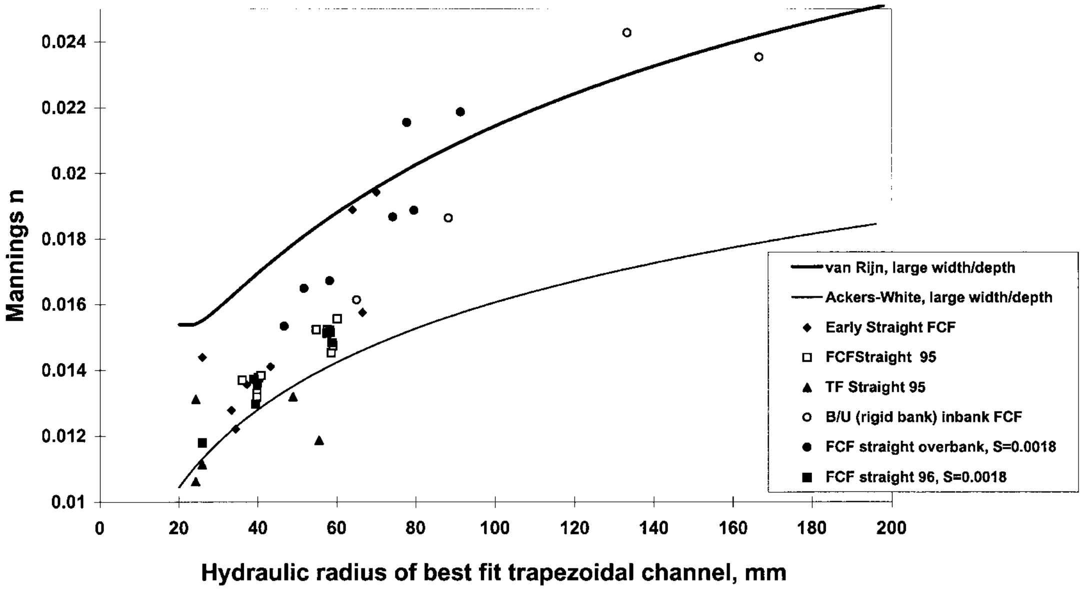

Fig. 3. Manning's n versus hydraulic radius, overview of Series C data.

WPB (White *et al.*, [23]) and van Rijn ([21]) methods. Both methods account explicitly for the effect of sediment transport and bedforms in flows where the threshold for transport is exceeded. Both methods show resistance to vary in the same sense as the data and, for the range of experimental conditions, their predictions encompass the observations. Visual inspection shows that the WPB method represents the shallower range of flows well but that neither satisfactorily predicts the overall observed variation.

Sediment transport

Figure 4 shows the variation of sediment concentration (mostly with a range of 150-450 ppm) with the hydraulic radius (range mostly about 30-90mm). In about half the overbank flow experiments, the measured sediment transport rates were sufficiently steady and the water surface slope was sufficiently uniform for the concentrations to be included in the test dataset. Data from rigid bank FCF experiments are added to the free-form channel data from the FCF and tilting flume, for water surface slopes within 10% of the FCF slope. Each free-form experiment typically had 4-8 independent sediment transport measurements.

In different experiments the flow approached uniformity of water surface slopes both above and below the FCF slope, a lack of bias which suggests that the transport data were not significantly affected by any trend towards deposition or erosion along the channel. Likewise the uniformity of channel planform and cross-section suggests that the slow bank erosion which occurred during the free-form experiments did not contribute significantly to streamwise sediment transport. The consistency between the rigid bank and free-form channel data in Figure 4, and the large width/depth ratios, reinforce this conclusion. The self-consistency of the overbank and bankfull flow data similarly indicate little effect from the interaction of the floodplain and main channel flows.

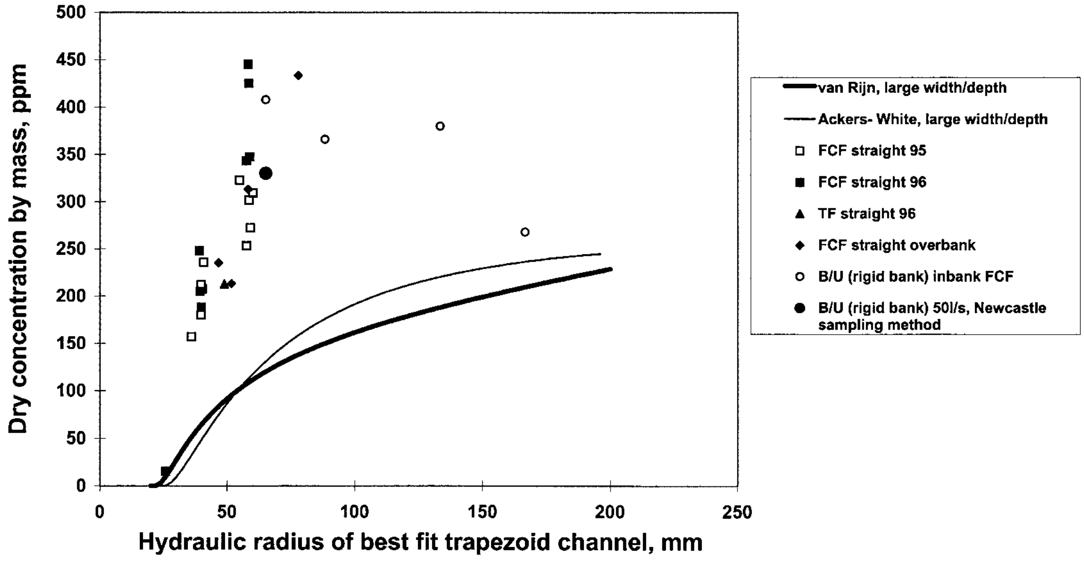

Fig. 4. Variation of sediment concentration with hydraulic radius.

The plotted data show a consistent increase of concentration with hydraulic radius, a variation compared in Figure 4 with the predictions of the WPB (Ackers and White [2]) and van Rijn [21] methods. Both methods also show an increase in concentration with hydraulic depth but underpredict the observed rate of increase. As a consequence the methods significantly underpredict nearly all the observed concentrations.

Extremal hypothesis

As noted earlier, preliminary experiments showed that initial channel screeds with rather higher width/depth ratios than predicted by the WPB method gave greater bank stability, at least for the range of bankfull discharges investigated. Since the method's flow resistance predictions are, on the whole, consistent with the observations, the deficiency in the stability prediction must lie with the sediment transport calculation or the extremal hypothesis (maximisation of sediment transport). For the experimental conditions, the sediment transport calculations significantly underpredict the measured concentrations and could therefore be the source of the faulty stability predictions. However, because of the underprediction of sediment transport, it is not possible to test the extremal hypothesis unambiguously. The validity of the hypothesis therefore remains unknown.

Bedforms

Sediment behaviour in terms of onset of transport and the development of bedforms was in good agreement with earlier work with similar conditions (e.g., Simons and Richardson [17]). Measurement of critical shear velocity u_{*c} (limited to an accuracy of 10%) gave values close to 0.018 m s^{-1}. The threshold depth for transport of the uniform 0.8 mm material was near 20 mm at the FCF slope. Above 20 mm depth, a plane bed with flow-parallel ridges developed. At bankfull stage in the 40mm and 70mm deep channels (corresponding to bankfull discharges of 25 and 45 l s^{-1} respectively), two-dimensional sand waves and flow-parallel ridges co-existed (Figure 5). Two-dimensional sand waves or two-dimensional dunes are recognised as a separate class of bedform by some authors. They are dunes having a length/height ratio larger than typical dunes but a wavelength significantly less than that of alternate bars (e.g., Best [6]). At greater depths, around 100 mm, the bedforms gave way to true dunes with some flow parallel ridges still present. The deepest FCF flows of 200-300 mm depth, investigated during the work with rigid banks (Myers and Cassells [13]; Knight and Brown [10]), were dominated by dunes and flow parallel ridges were absent. The upper plane bed condition was not achieved in any experiment. Likewise, the size of the sediment was sufficient that ripples were never clearly observed, even near threshold conditions. Figure 6 compares the FCF bedform data with data from other experiments, largely in fixed bank flumes.

Alternating bars were seen to develop in the FCF only at high width/depth ratios from either the flat bed or two-dimensional sand wave conditions, and only after 10-24 hours. At steeper slopes in the 2.5m wide tilting flume, alternate bars appeared

Fig. 5. A general view of the FCF main channel looking downstream and showing typical developed two-dimensional sand waves and flow-parallel ridges.

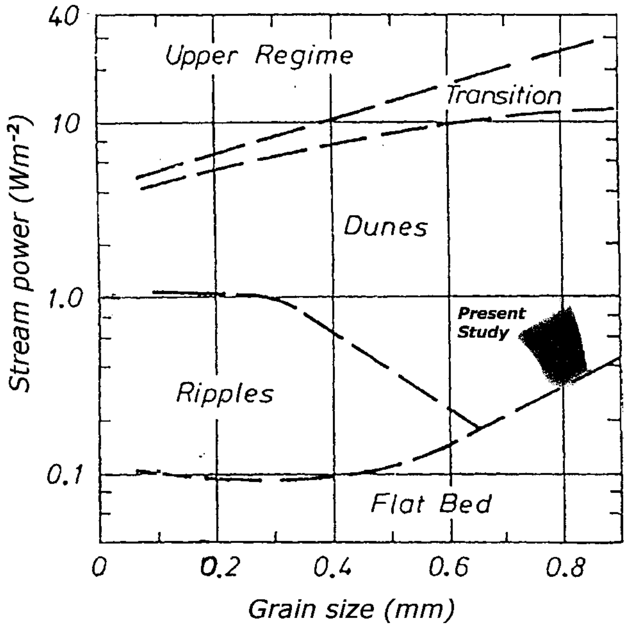

Fig. 6. Relation of bed form to stream power and grain size of sediment. (after Simons and Richardson, 1961).

more rapidly. The onset of alternating bars as a function of width/depth ratio, slope and particle diameter was well predicted by Jaeggi [9]). The steep (slope=3.6×10^{-3} m m^{-1}) tilting flume experiments of 4 l s^{-1} and the FCF experiments of 10 l s^{-1} provide good examples of the initiation of alternating bars and meandering. The experimental data used in the analysis of this paper refer only to the period preceding bar formation and planform changes. The sand waves and dunes formed within minutes in most cases. Hydraulic roughness, expressed as Manning's n, was established in minutes or tens of minutes, both at the start of the experiment and upon increasing the flow from bankfull to overbank. Nevertheless the development of the bed features was asymptotic and presumably affected by the evolving width and planform. In the strictest sense, therefore, only a few of the experiments could be said to have reached an equilibrium state of bedforms.

Bank erosion rate

The erosion rate was obtained by measuring width change over time and obtaining channel area from the automatic bed profiler at the end of the experiments. Bank erosion rate per unit length of channel, non-dimensionalised with sediment transport rate per unit channel width, is plotted against width/depth ratio in Figure 7, indicating that bank stability is greater in channels of higher width/depth ratio. The non-dimensional term provides a fairer comparison of stability between channels with different transport rates; a straight channel with a low transport rate would be expected to have a high degree of bank stability (Yalin and da Silva [26]). Experimental error is shown for 60% confidence limits resulting from propagation of errors in the input terms.

Erosion rate along one bank per unit length is given as a function of stream power per unit area, non-dimensionalised by acceleration due to gravity, in Figure 8. This approach was prompted by Nanson and Hicken's [14] analysis of field data on the expansion of meandering channel cutbanks. That analysis found a stronger link between erosion rate and stream power per unit length than stream power per unit area but the opposite was found for this study. It is important to note that the erodibility of the bank sediment has been ignored but, however this may be defined, it should be constant as the experiments were all performed with the same loose sediment. Of particular interest, erosion rates during overbank flows are similar to those for bankfull flows of the same stream power per unit area.

The dimensions of the axes in Figure 8 are identical, which implies a search for a linear relationship. However, the results do not convincingly define a straight line and the scatter of data points in Figures 7 and 8 is larger than can be accounted for by the estimated experimental error. This implies that width/depth ratio and stream power per unit area are not the only important factors affecting bank erosion rate. Stream power is dissipated mainly within the flow, rather than as work done on the bed and banks, and the proportion of this power expended on erosion or sediment transport is likely to depend in a complex way on such factors as flow symmetry and Reynolds Number. This is a weakness of using stream power as an independent variable affecting the boundary. However, tests using the alternative variables of shear stress, shear velocity and sediment transport per unit width (as predicted by the Ackers and White method) showed even greater scatter.

Conclusions

Experiments relevant to the regime behaviour of a straight loose-boundary channel in a fixed floodplain were carried out in a large laboratory flume, incorporating bankfull and overbank flow conditions. The experiments considerably extend the range of laboratory data, in terms of channel scale, discharge and width/depth ratio and represent the establishment of a methodology for

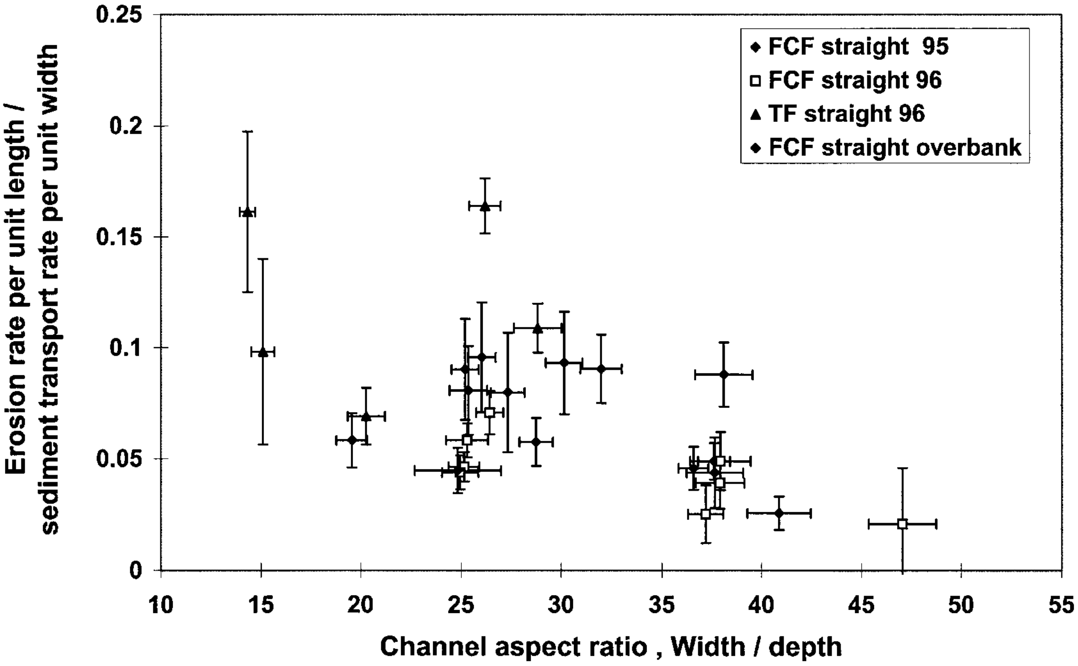

Fig. 7. Bank erosion versus width/depth ratio.

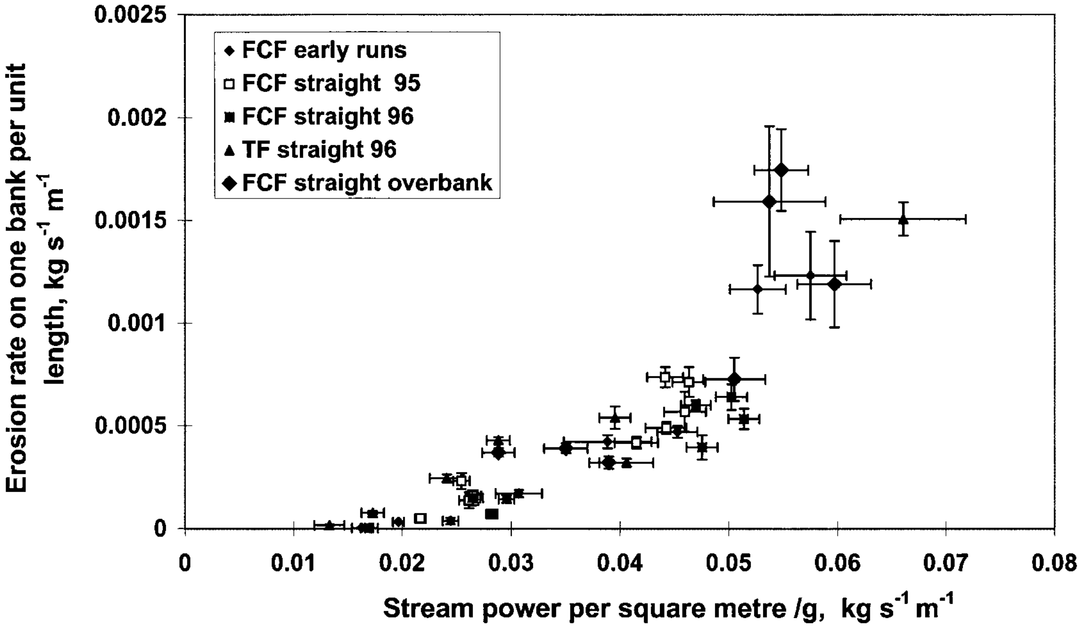

Fig. 8. Bank erosion rate as a function of stream power per unit area.

overbank flow studies in loose-boundary channels. Considerable care was taken to ensure uniform quasi-steady flow conditions, as a basic requirement for assessing regime theory.

Bankfull, near-regime channels were found to be wider and shallower than predicted by the WPB rational regime approach. This is consistent with experiments in smaller scale channels. The friction data for these mobile channels are consistent with theory, but it was found that sediment transport theory persistently underpredicts the measured rates. These observations, of course, influence the rational regime predictions upon which the initial channel sections were based. Thus the extremal hypothesis of the maximisation of sediment transport rate could not be tested unambigiously. Nevertheless, straight regime channel conditions were predicted reasonably well, although it was necessary to allow for bedform effects when assessing cross-sectional stability. The observed bedforms are consistent with the Simons and Richardson [17] diagram of bedform domains. For these experiments they are located just above the plain bed domain and consist of two-dimensional sand waves.

Overbank flow stability was poorer. Rates of bank erosion were measured and constitute unique widening data for the main channel under overbank flow conditions. They show a much greater rate of widening than for the bankfull flow channels. These data may provide a basis for estimates of channel bank erosion in prototype channels, although it remains to be established how this can be expressed in the context of the prototype.

Overall, the results confirm a good ability to predict stable channels for inbank flows but indicate that revised approaches are necessary for two-stage loose-boundary channels subject to significant overbank flow. Results for additional experiments carried out with meandering free-form channels are under analysis and will test these conclusions for the meandering planform.

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