Boundary shear distribution in open channel compound

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In § 22 the Authors rightly state that the shear distribution is distinctly non-uniform in character, and this agrees well with our findings.

28. Concerning § 23, the Authors' results bear out the points that maximum side and bed stresses in the web section occur some distance from the free surface and approximately mid-way between the centre and corner of the bed respectively, but their results do not support the final point that the maximum shear stress on the bed of the flange occurs at the junction. Referring to Fig. 6 it may be seen that the point holds for runs 1–3 but not for runs 4–5. It would appear that as depth is increased, so the maximum stress on the bed of the flange moves from the junction. The same effect may be taking place in the compound rough runs as well.

29. The interaction between the web section and the flange is bound to affect the results. Sellin[10] and Townsend[11, 12] have shown that a bank of vortices is generated at the sharp corner and that then they shed in the downstream direction. Momentum transfer between the web and flange sections is inevitable and may depend on the depth of flow. It may also affect the position of the point of maximum shear stress. The Authors' comments on this would be appreciated.

30. A typical result, from experiments carried out on a channel of complex cross-section at the Civil Engineering Department, Queen's University of Belfast, is shown in Fig. 10. When a Preston tube of 0·0716 in. o.d. was used, the result agreed with the Authors' conclusions on position of maximum shear on the side and flange bed, although the maximum bed shear in the web was at or near the centre line of the web. This difference may be due to assymetry in our model.

31. In § 25 the Authors make some interesting comments on the proportion of drag taken by each section at different depths. The Authors found that, in the case of the compound rough runs, the web drag always exceeds that of the flange, whereas in the compound smooth runs the depth was influential. Fig. 10 shows a situation where web shear is greater than that of the flange. These conclusions raise interesting questions concerning the relevance of the concept of momentum transfer in these contexts and also concerning its variability with depth, roughness, channel form and other parameters.

32. Referring to Table 1 and § 26, it can be seen that computed and measured shear stress agree fairly well except for runs 1 and 6 where the errors are 21·1% and 15·8% respectively. These errors are positive, suggesting that the Preston tube is reading high.

33. It might be useful to make a tentative suggestion as to the cause of these rather large errors. It has been suggested by Preston[13] that the maximum extent of the region in which local dynamic similarity may be expected to hold is approximately one fifth of the boundary layer thickness. As the Authors used a tube of 0·25 in. o.d. at depths of 0·828 in. and 1·16 in. on the flange on runs 1 and 6 respectively, it can be seen that the region of similarity was exceeded.

Paper published: *Proc. Instn Civ. Engrs*, 1971, **49** (Aug.) 417–430.

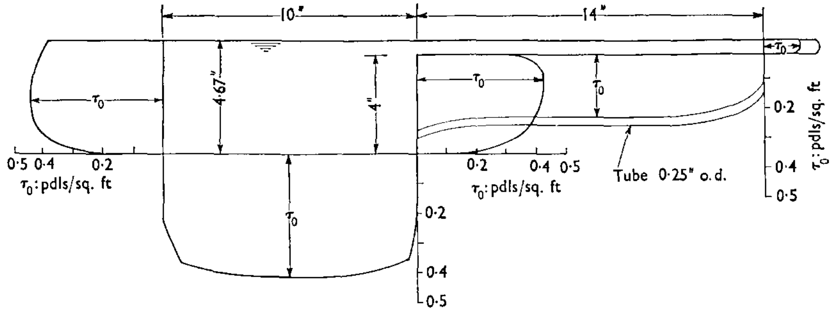


Fig. 10. Typical shear stress pattern obtained using tube of 0·0716 in. o.d. except where stated

34. Figure 10 shows the shear stress pattern yielded by using 0·25 in. o.d. and 0·0716 in. o.d. Preston tubes on the floodplain zone. Shear stress measured using the 0·25 in. o.d. tube gave higher readings than those obtained using the smaller tube. This brings out the importance of not exceeding the region of similarity. It is for this reason that it may be preferable to use hot-film anemometry, with flush-mounting probes, for measuring shear stresses at low depths of flow.

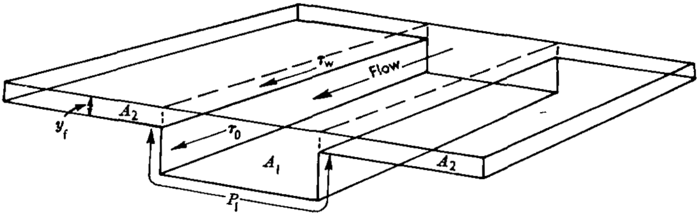
35. From experience using Preston tubes of different diameters, it was found that a tube of 0·25 in. o.d. was too large and caused large fluctuations due to disturbances, and hence errors up to 25% less than computed from energy considerations. This would have been larger, had it not been for the compensating effect of high floodplain readings. Using a tube of 0·0716 in. o.d. cut this error to 2·5%. Steele and Pierce,[14] have had similar experience, concluding that a tube of 0·0404 in. o.d. was most suitable for work in water. These suggestions may explain the Authors' errors between measured and computed shear stress.

Professor P. Novak, University of Newcastle upon Tyne

When extending the argument in the theoretical part of the Paper the use of the parameter λ (or another similar expression) in equation (5) is valid only up to a certain limit for concentrations of the roughness elements. According to experiments carried out at Newcastle this limit seems to be about 60%, which is much higher than the value for the dense roughness arrrangement reported by Ghosh and Roy.[3] The variability of λ is equivalent to a variation of the additive term in the Prandtl–Karman velocity distribution equation. Although λ characterizes suitably the rough boundary surface it does not solve the problem of zero datum, particularly for very high concentrations.

37. In the experimental procedure, considering the relatively small length (28 ft) of the flume, its width and the discharges used, I have doubts as to what extent uniform flow conditions for all discharges were established with a constant slope. The Authors do not mention a downstream depth control; in my experience it is extremely difficult to achieve uniform flow in a flume of the quoted length without a downstream control and/or a variation of slope. I wonder to what extent the fact that the flow was practically uniform could account for the not serious differences between the measured and calculated mean shear stresses in Table 1.

38. From the sediment motion point of view it should be born in mind that the shear stresses plotted and used in Figs 8 and 9 for point measurements are time mean shear stresses at the respective points of the boundary and that taking a relative intensity of turbulence $\sigma/\bar{u}$ as approximately $\frac{1}{6}$ and $(u_{\max}-\bar{u})/\sigma=3$ gives a ratio of $\tau_{\max}/\tau$ as high as 2·25.



A_1	cross-section area of flow in centre channel
A_2	cross-section area of flow in one floodplain
P_1	wetted perimeter of centre channel
τ_0	wall shear stress at a point
τ_w	fluid shear stress at interface
y_f	uniform depth on floodplain
s	channel slope (positive downhill in flow direction)

Fig. 11. Generalized model of river channel flanked by floodplains

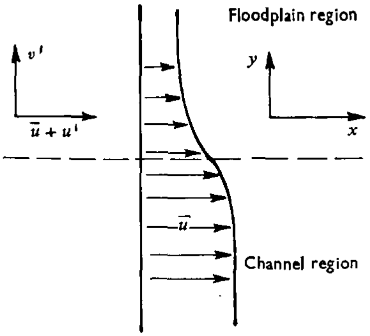
39. It would have been interesting to evaluate and compare the mean shear stresses on various parts of the cross section separately, i.e. the bed and sides of both the web and flange part of the section. An inspection of the graphs in Figs 6 and 7 seems to indicate that for the web section the mean shear stress on the walls at lower depths is approximately equal to the mean shear stress on the bed. This is to be expected and is borne out by experimental evidence for a depth to width ratio of two in a rectangular channel of equal roughness on the walls and bed.

40. The Authors attribute the shifts and the degree of non-uniformity of the shear stress distribution to circulatory flow. This is no doubt correct but does not fully explain, for example, the fact that for the rough section the maximum shear stress on the bed occurred at the centreline of the channel, whereas for the smooth channel it occurred some distance away from it. This is contrary to the results reported for a simple section (using the same measuring technique) in reference 3 and the results are not consistent among themselves, e.g. for the rough surface the maximum did not occur at the centreline for the intermediate depth 0·53 ft, whereas for the smallest depth in the smooth section the maximum was almost in the centre. The experiments with a smooth and rough boundary do not seem to be fully comparable in this respect as with the exception of one experiment the depths in all the rough boundary experiments reported in the Paper were bigger than the maximum depth in the smooth channel. Would the Authors state to what extent the bed distribution of the shear stress shown in Figs 6 and 7 was really symmetrical about the centreline and explain in detail the positioning of the dynamic pressure tube in relation to the individual roughness elements and the channel bed for measurements made in the rough channel.

Dr R. H. J. Sellin, Department of Civil Engineering, University of Bristol

The Authors' apparently successful measurement of boundary shear stress in a channel of compound cross section throws new light on a problem that has concerned me. This was essentially an experimental investigation into steady flow in a prismatic laboratory channel shaped to represent a river–floodplain combination.[15] This is in principle the same cross section geometry as that studied by the Authors but in my case particular attention was paid to shallow submergence depths on the floodplain. Such depths lead to wide differences between the average velocities in the different regions of the cross section and this velocity difference generates a strong lateral momentum transfer mechanism between the flow in the river channel and that on the floodplain.

42. It was found that this momentum transfer mechanism exercised a controlling influence on the flow in the channel section, because when a thin impermeable flood wall was introduced along the model river banks (shown dashed in Fig. 11) an increase



u time average velocity (component in downstream direction)
u′ transient velocity component in downstream direction
v′ transient velocity component in perpendicular direction (time average velocity component in this direction zero)

Fig. 12. Mean velocity distribution just below the free surface

in velocity resulted in the channel section and a corresponding decrease over the floodplain.

43. This effect has also been noticed by Russian engineers and they call it the 'kinematic effect'. The many publications on this originating from the Moscow Institute of Railway Engineers are listed in a paper by Zheleznyakov.[16]

44. In my experiments a qualitative indication of the strength of this essentially two-dimensional transverse circulation was obtained by time exposure photography of surface particles. A quantitative assessment of the effect of these vortices on the resistance to flow in the channel could not be made directly without detailed wall shear stress measurements which were then not attempted.

45. The classical resistance equation for uniform steady flow in a channel, from which the Chezy formula is usually derived, can be modified to apply to one region only of the cross section if a momentum transfer term is included acting across the imaginary dividing surfaces (water/water interface). Considering unit length of such a channel (using the notation in Fig. 11) and restricting attention to the deep centre section the force inducing the flow is $\rho g A_1 s$ while that resisting the flow is

$$\int_0^{P_1} \tau_0 \, \mathrm{d}P + 2\int_0^{y_f} \tau_w \, \mathrm{d}y$$

and these expressions may be equated for steady flow giving

$$\rho g A_1 s = \int_0^{P_1} \tau_0 \, \mathrm{d}P + 2\int_0^{y_f} \tau_w \, \mathrm{d}y \quad . \; . \; . \; . \; . \; . \quad (9)$$

46. The fluid shear stress term τ_w includes the so-called Reynolds stresses due to the turbulent interchange of momentum as well as the purely viscious shear stresses. From the Navier–Stokes equation[17] the local shear stress τ_w at the fluid interface shown in Fig. 12 can be evaluated in the form

$$\tau_w = \mu \frac{\partial \bar{u}}{\partial y} + \rho \overline{u'v'} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

47. The viscous shear stress term $\mu \partial \bar{u}/\partial y$ can be evaluated for the Pitot tube velocity traverses given in reference 15 (Fig. 7) at $7{\cdot}5 \times 10^{-5}$ lb/sq. ft assuming a water temperature of 15°C. This is approximately 1/500 of the Authors' value of τ_0 measured at the interface angle under similar flow conditions (Fig. 6, run 1). Thus

the viscous shear stress term can safely be neglected and equation (10) re-written as

$$\tau_w = \rho\,\overline{u'v'} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (11)$$

48. Attempts to measure this quantity by dye diffusion techniques have been made by Townsend.[12] This work measured turbulent energy levels in this zone but did not present data in a form suitable for correlation which is necessary if the product term $\bar{u}'v'$ is required.

49. At present it would seem physically possible to construct a turbulence probe consisting of two mutually perpendicular hot film elements (probably the coated quartz fibre type would be best) which could be made to yield values of $\bar{u}'v'$ in a suitable laboratory flume.

50. By combining this technique with wall shear stress measurements similar to those made by the Authors it should be possible to evaluate all the terms in equation (9). This would enable a detailed investigation of the kinematic effect to be made under all conditions of floodplain submergence and so provide a tool for measuring the effectiveness of proposals to increase the flood capacity of river channels through model investigations. It might also enable an allowance to be made for the kinematic effect in flood routing operations.

Messrs S. Ghosh and S. B. Jena

We are grateful to **Mr Myers** and **Dr Elsawy** for pointing out the discrepancy with regard to the location of maximum shear stress on the bed of the flange for runs 4–5, which can be due either to the reasons attributed or erroneous observations, since in the subsequent series of runs with denser roughness distribution, no such shift has been noticed.

52. We agree with the observation of Mr Myers and Dr Elsawy that there will be considerable interaction between the flow in the web and flange section due to momentum transfer and consequent readjustment of shear stress distribution (however, the pattern remains the same). The indirect effect of this interaction has been estimated by introducing an apparent shear over an added solid boundary equivalent to the wetted perimeter of the web and flange section, proceeding on lines suggested by Toebes and Sooky.[18] Dimensionless plots of the relevant data indicate that interaction loss first increases and then decreases with increase of flow depth over the flange section.

53. We acknowledge the suggestions concerning the effect of Preston tube diameter on the dynamic pressure. We did not know of the work of Steele and Pierce.[14] The comments will help planning of future studies.

54. Regarding the comments on λ by **Professor Novak**, we should like to clear the confusion caused by the word 'dense' roughness arrangement used by Ghosh and

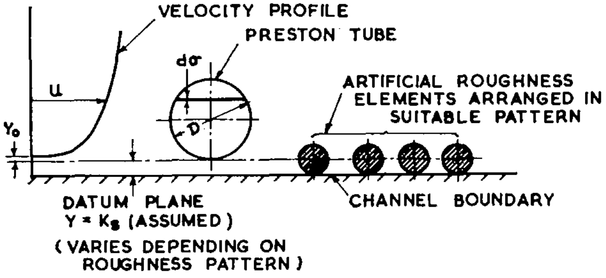


Fig. 13

Roy.[3] The word dense has been used simply to identify the three patterns of roughness arrangement used. We agree with Professor Novak's observation regarding the validity of expression (5) up to roughness concentration of 60%. The problem of defining a suitable datum plane has concerned us. The Preston tube has been located at a hypothetical datum plane equal to the Nikuradse sand roughness height from the channel boundary (Fig. 13) and this has satisfactorily solved the problem of zero datum location.

55. We concede that it is not possible to ensure truly uniform flow in such a short experimental flume. Nevertheless, because of good energy dissipation and transition arrangements at the upstream and downstream tail gate control, nearly uniform flow is established at the test section. The differences between the measured and calculated mean shear stresses in some of the runs are probably due to the use of a relatively large diameter Preston tube as pointed out by Mr Myers and Dr Elsawy and possible lacuna in the assumed velocity distribution.

56. Professor Novak has pointed out some inconsistency in the location of maximum shear stress in simple section as reported by Ghosh and Roy.[3] This is no doubt correct. However, an extension of the same argument in the case of compound channels is not likely to be valid. The location of maximum shear stress is related to the velocity gradient at the location where shear measurement is undertaken. The velocity contours in turn are affected by the circulatory flow which starts with a sharp change of boundary, roughness elements and as soon as the depth:width ratio is altered. The circulatory flow in turn affects the pressure gradient. The insertion of a Preston tube also slightly distorts the velocity field. All these factors and the fact that total and static pressure tubes were separated while collecting the experimental data, make it likely for some inconsistency in the result to have crept in.

57. Professor Novak's question of the degree of symmetry of the bed shear distribution is very pertinent. It is impossible to ensure symmetrical flow in the whole crosssection. Nevertheless, a better idea of the symmetry can be had from the velocity contours. On examination of the relevant velocity contours, it can be said that the degree of symmetry over the bed of the web is good although the same is not true for the bed at the flange section and at the upper region of the central core of fluid.

58. Regarding the location of the dynamic pressure tube, it is apparent that the tube has been placed either at the top of the roughness elements or at the channel bottom, although for analysis the dynamic pressure tube is supposed to be positioned at the hypothetical datum plane (§ 54). Consequent error in pressure response is believed to be negligible. The result obtained by this concept in the subsequent series of runs with increasing roughness concentration is observed to be satisfactory.

59. We are grateful to **Professor Sellin** for his suggestions. The interaction of the flange and web section can be taken care of quantitatively by dividing the flow at the horizontal junction on the lines suggested by Toebes and Sooky[18] and hydraulic subdivision of flow along that line has been found to be satisfactory.

60. As regards the measurement of τ_w', the problem ultimately reduces to the simultaneous measurement and correlation of the two velocity fluctuations, since the contribution of viscous shear is negligible. We are aware of the existence of quartz coated hot film turbulence measurement probes and accessory instruments but have not yet acquired such facilities. It has not yet been possible to study fluid turbulence.

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