Paper No. 6265

Some aspects of the design of hydraulic structures in alluvium†

by

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Discussion

Mr A. M. R. Montagu had found some difficulty in reading the Paper, for reasons which he would explain. Before doing so, however, he commented on the references given on p. 162.

75. That part of reference 3 which dealt with the standing wave or hydraulic jump was based upon—one might almost say reprinted from—preceding Central Board of Irrigation Papers Nos 4, 6, 7, and 10 (see references 11, 12, and 13 below and reference 10 at the end of the Paper). Presumably, in the tenth reference on p. 162 the Author was drawing attention to the 1st edition of C.B.I. Publication No. 7. Mr Montagu pointed out that the 2nd edition was so much at variance with the 1st edition (e.g. the regrettable omission of all references to Blench's examination of the "loaded trough") that it could with advantage be the subject of an additional reference number.

76. The design principle (*c*) in § 1 might be more clearly stated as: "The velocity at exit or residual head should be less than that required to move the material of which the bed is composed".

77. On gently sloping straight-line glacis, the standing wave formed (see § 2) a little *higher* (and therefore "safer") than the point given by the formula derived from horizontal flow[14]. The difference was small and probably arose from the phenomenon of the "loaded trough", upon which further investigation was desirable. It was certainly the case on the "semi-parabolic" glacis, of which there were so many examples in the Punjab, particularly on the Western Jumna Canal[13].

78. Referring to § 6 and Fig. 1, Mr Montagu observed that no standing wave could form on a horizontal frictionless floor[10,12], even if such a floor could exist. The hypercritical stream would continue indefinitely.

79. Equation (1) as given by the Author was basic[10] and could be given in a dozen or more forms (including a dimensionless form), each of which was of more practical use.

80. In noting the reappearance of the word "frictionless" in § 9, Mr Montagu further pointed out that the slope of the glacis would constantly accelerate the hypercritical stream. In the same paragraph the Author had introduced the term "specific energy". Mr Montagu suggested that adherence to the more generally recognized term "energy of flow, E_f" would avoid confusion. Indeed, the Author himself had used it later in the Paper. It was clearly defined in the expression $E_f = D + V^2/2g$, which showed its value to be the intercept between the bed of the channel and the total energy line[10,11,12,13,14].

81. In Fig. 2, x and y were intended to be the co-ordinates of a point (marked by a dot) in the water surface. It had to be realized that the dimension y was inaccurately marked in the Figure, before the appearance of the final D_1 in the first two expressions in § 10 could be understood. In any case, Mr Montagu suggested that the reasoning in § 10 was unnecessary, since the simple equation $E_f = D + V^2/2g$ would enable one to trace the profile of any stream, whether hypercritical or subcritical. Numerous author-

† Proc. Instn civ. Engrs, vol. 10, p. 145 (June 1958).

ities had produced diagrams, all of which were quick to use and well within the limits of accuracy of hydraulic observations or design. The best known were those given in references 10 and 12, from which Khosla had produced his standing wave diagram[3].

82. Mr Montagu had never heard of the method given in § 11 of ascertaining the position of the standing wave on a glacis. It had no theoretical basis and could give completely misleading results. There were half-a-dozen theoretically sound methods; Mr Montagu himself used only the method given in references 10 and 13, which was not only the quickest and simplest, but also the most flexible, for it covered all types of problems, including the "loaded trough" conditions, with only one diagram.

83. The diagram in Fig. 3 had obviously been printed in an incorrect attitude, since the line labelled "percolation gradient" clearly could not be horizontal. Mr Montagu suggested that a better label would be "pressure gradient".

84. There was no mention in the Paper of the effect of the glacis slope on the subcritical stream surface. This was an important omission, but the subject had been treated at length in reference 12. Had the Author calculated the change in elevation, from point to point, of the subcritical stream surface, due to the sloping glacis (see § 18)?

85. There was evidence of confused reasoning in § 20. The non-dimensional forms of the basic standing wave formula were Crump's contribution to reference 10. There was no need to confine attention to, and to derive fortuitous relations for, the particular case of the standing wave occurring at the toe of the glacis. Moreover, Mr Montagu suspected that the bed level of the flume was the same both up-stream and down-stream of the experimental weir, and that the weir and channel were of the same width. Only if that was so could any sort of relation be established between quantities which were unrelated in the general case. It should be remembered that for a given value of q there was a unique value of D_2 for each value of D_1 (or V_2 for each value of V_1). The only rational non-dimensional quantity was D/D_c.

86. In Fig. 5, the value of h could be made anything (between limits) by adjusting the width of the throat of the flume. D_2 on the other hand, was a characteristic of the channel down-stream, and could be varied (within limits). The two bore no relation to one another in the general case.

87. The Author's H appeared to be $E_{f2}+H_L$. But E_{f2} was related to D_2 and H_L was not. It followed that equations such as $E_{f2} = C.H^{0\cdot155}$ and $C = 0\cdot734\,q^{0\cdot57}$ were only casual relations peculiar to the particular weir system under consideration.

88. What was the origin of the "coefficient of 3·40" in § 21? The value of K in the free-fall formula $q = KH^{3/2}$ was 3·08880 . . . and was fixed. The value of q would invariably be slightly reduced by friction through the weir. But if any calculation resulted in a value of K higher than 3·0888 then H was being measured in the wrong place, so introducing an error whose magnitude was difficult to assess. For weirs having the profiles indicated in the Author's sketches, the position of the critical section would be indeterminate. And herein lay the true explanation of the phenomenon "observed" by the Author in § 26.

89. Mr Montagu believed that the theoretical derivation, the limitations, and the possible sources of error of the formula $q = KH^{3/2}$ had already been fully established. Apparently, Crump's work on the subject was not yet universally recognized.

90. In § 24 the Author had introduced a factor to deal with the "coriolis" effect, which he had hitherto ignored, but had given no reason why the resulting modification in the kinetic energy should amount to nearly 29% (the difference between $V^2/2g$ and $V^2/50$).

91. Reference 13 dealt with the vertical component of velocity at any point on the glacis and its persistence after impact in the standing wave. It also reviewed the devices adopted by various authorities for dealing with the residual energy. Mr Montagu commended this publication to the Author's attention. He felt that the arguments now advanced in §§ 27 to 34 were based upon an erroneous interpretation of the phenomenon mentioned in § 26, to which he had already referred.

92. In conclusion, Mr Montagu pointed out that recorded experience showed that scour below falls (§ 36 *et seq.*) could be practically eliminated by suitable design.

Ordinarily a little local action occurred where masonry changed to earthwork, but nothing that a little ballast could not cure.

Mr P. O. Wolf wished to add to the Author's references two more[15, 16] in which the problems of flow over weirs, and of energy dissipation and scour down-stream of spillways, were discussed in a manner of general interest to students of Mr Bunyan's Paper.

94. One of the lessons to be learned from those references, as indeed from the Author's references[1, 2], was that the formulae derived from model tests should not only relate variables in a significant way, but should be dimensionally consistent. For example, the formulae of §§ 22 and 23 led to a combined expression $E_{f2} = 0{\cdot}734\, q^{0{\cdot}57} H^{0{\cdot}155}$ which was not homogeneous. Perhaps the Author could say if the last digit in one exponent could be altered slightly so that a homogeneous formula could be deduced,

$$E_{f2} = \left(\frac{10{\cdot}76}{g}\right)^{0{\cdot}282} q^{0{\cdot}565}\, H^{0{\cdot}155}$$

which, however, still did not have the appearance of a generally applicable law to be used for extrapolation.

95. The kinetic-energy factor of $\alpha = 64{\cdot}4/50 = 1{\cdot}29$, which defined the lack of uniformity of the velocity across the section down-stream of the jump (§ 24), while unusual, seemed amply justified.

96. § 26 touching on the dissipation of energy in continuously accelerating flow over a weir, might be expanded to explain flow over a rounded outfall in terms of potential flow. If a flow net was drawn for the area near the crest of a well-designed high-coefficient weir, a considerable part of the crest would be found to be at a low pressure. The pressure gradient providing acceleration towards and over such a weir crest was, therefore, larger than with a low-coefficient weir on the crest of which (assuming proper design) the pressure might be nearly hydrostatic. Down-stream of the crest, however, the high-coefficient weir would show an adverse pressure gradient, resulting in a retardation of the flow such as would not occur below the low-coefficient weir crest. Particularly at high rates of flow, when the retardation might be appreciable, the energy dissipation in that reach would be quite useful. On the other hand, the energy dissipation in the continuously accelerating flow over the low-coefficient spillway would be even less than in "normal" flow. Where the jump was near the crest, perhaps h or $2h$ below it, and the bulk of energy dissipation up-stream of the jump would occur in that pressure-recovery area, Mr Wolf would have expected a difference (§ 27) of practical value.

The Author, in reply, regretted that Mr Montagu had found difficulty in reading the Paper, for this had apparently led him to misunderstand its purpose and to base many of his criticisms on misconceptions.

98. If, as Mr Montagu had stated, the relevant parts of reference 3 were based upon or ". . . almost reprinted from . . ." references 11, 12, and 13 and C.B.I. Publication No. 7, this would seem adequate reason to quote one omnibus reference rather than several; especially since the former contained acknowledgements of previous sources. However, the Author apologized that due credit had not been specifically given to Mr Montagu for his previous work on this and allied subjects—notably the references given above. The omission had not been intentional.

99. If a structure was large enough, or unusual enough, it would almost certainly justify a specific hydraulic model study. In such an event design curves or rules produced by Mr Montagu, or by the Author, or by anyone else would be of value only when designing the model. A fuller and more complete answer could be obtained from a study of the model itself under the anticipated operating conditions. However, in many cases such a study could not be justified and it was in those cases that the designer's work was made much easier if he could refer to design curves and rules derived from the study of structures, and models of structures, basically similar to that which he had in mind.

100. From considerations of permissible afflux, anticipated retrogression of

down-stream bed levels, discharge intensities, and other data, he must determine the level at which he would place the crest of his weir. To do so he must assume certain discharge characteristics for the weir which would depend upon the crest form, amongst other factors. From previous experience or from model tests on similar weirs he should be able to make a reasonably accurate estimate, but he was rarely likely to know precisely —certainly not to four places of decimals! Therefore if he assumed a discharge formula of the type $q=C_d\, h^{3/2}$ he would not introduce errors greater than those inherent in his basic assumptions. Having made those assumptions and estimated the stage discharge relations of the channel down-stream, after allowing for possible retrogression of bed levels, he must decide on the best possible apron level (usually the highest possible because the cheapest), which would ensure that at no time would the jump leave the glacis toe and run off the apron. At the same time he would wish to make sure that, with the above criterion satisfied, his structure would, in addition, be safe against uplift pressures and safe from failure due to piping; and finally that no excessive scour would develop off the end of the apron.

101. For any structure where the hypercritical jet flowed between parallel walls, Fig. 8 could be used to determine apron levels, the position in which the jump formed could be interpolated from Fig. 9, the shape of the jump profile could be interpolated from Fig. 4, and Fig. 15 could be used to determine whether serious scour was likely to develop (i.e. if the Froude Number of the flow leaving the structure exceeded, by much, the values indicated, then troublesome scour would develop, allowance being made for the nature of the bed material).

102. Within this context it could be seen that many of the points raised by Mr Montagu were not relevant to the Paper, which did not attempt to deal with the problems arising in a flumed structure in which the jet was converged horizontally.

103. It was quite misleading to say that a hydraulic jump could not form on a frictionless floor, assuming such a floor to exist. It could not form by itself, but it could very easily be made to form by artificially raising the tail-water level. In practice tail-water levels were dictated by the stage discharge relations of the channel down-stream and not by the frictional properties of the structure's apron. However, the use of the word "frictionless" had been, of course, intended to convey the meaning that the effect of friction was being ignored for the moment and should, perhaps, have been printed in quotes.

104. Fig. 2 showed that as the jet moved down the glacis it became thinner—because it became faster—so it was hardly necessary to emphasize the obvious, i.e. that the jet accelerated down the slope.

105. It had not been suggested in § 11 that the theoretical position of the jump obtained as described would give an accurate answer. On the contrary it had been pointed out that the theoretical position so obtained differed considerably from the true position. But that the method had been used as a starting point from which to determine jump position, Mr Montagu would be able to ascertain by consulting references 3 and 4.

106. The Author was grateful to Mr Montagu for pointing out that Fig. 3 had been printed in an incorrect attitude. In its correct position the apron shown would be horizontal.

107. In § 84 Mr Montagu was, presumably, referring to Fig. 4. The jump profiles shown were typical of those traced by observation on the models. The elevation of the subscritical stream surface up-stream of the weir crest had been calculated from point to point, for the purpose of drawing Fig. 2. Reference 12 dealt with fluming and while it was a very interesting and valuable publication, it was not directly relevant to the subject matter of the Paper.

108. The Author found it difficult to reply to an unsupported accusation of confused reasoning, except to state that no case had been made that required answer. Attention had not been confined to the case of the jump forming at the glacis toe (§§ 30 *et seq.*), but he (the Author) considered it to be the most important case because : (a) it was the condition of maximum energy dissipation; (b) it was the limiting case between safety

and the possible disaster that would be invited if the jump was allowed to run off the apron; and (c) if the tail water was higher than that which would just hold the jump at the toe, the jump would move up the glacis, and this represented a *safer* condition.

109. In Fig. 5, h had been corrected for velocity of approach, and hence the elevation of the up-stream bed levels, within limits, would have little practical significance. The relations between h and D_2 were valid, as used, in the case of any structure where the hypercritical jet flowed between parallel walls.

110. H was defined in § 20 and was shown in Fig. 5, and the relations $E_{f2}=CH^{0 \cdot 155}$ and $C=0{\cdot}734\, q^{0 \cdot 57}$ were valid for all structures of the general type defined above.

111. In § 88 Mr Montagu would appear to be thinking in terms of a flat-topped broad-crested weir. However, it would be appreciated that in any river carrying sediment in any quantity, the greater the afflux caused by the construction of a weir, the greater would be the interference with the regime of the river, resulting in "silting" up-stream of the weir and retrogression of bed levels down-stream. It had been known for some time that by rounding off the weir crest, higher discharges could be passed for a given elevation of up-stream energy of flow above crest level (i.e. h), and hence that *higher velocities in the up-stream channel could be obtained*. The use of such a "high coefficient" weir could therefore reduce the quantity of material trapped up-stream and reduce the amount of retrogression down-stream. The discharge characteristics of such a weir, if put in the form $q=C_d\, h^{3/2}$, would result in values of C_t much higher than 3·0888.

112. The kinetic energy within the greatly disturbed flow down-stream of a jump clearly could not be $V^2/2g$, which presupposed steady uniform flow. As a safety precaution it had been considered advisable to make allowance for the "coriolis" effect and the value $V^2/50$ had been chosen after reference to C.B.I. Publication No. 7 (2nd edition), to which Mr Montagu had referred. It was stated there that a kinetic energy factor of 1·26 had been measured in a trapezoidal channel down-stream of an expansion. A value of 1·29 down-stream of a jump was not considered excessive. (See also discussion on reference 4.)

113. Regarding Mr Montagu's remarks in §§ 91, 92, a quotation from C.B.I. Publication No. 10[13], which had been compiled by Mr Montagu and which he had commended to the Author's attention, was apposite. Referring to the problem of erosion of the bed and banks of a stream below a fall, the text (at p. 2) read: " . . . but it is only of recent years that engineers have claimed understanding of the phenomena and have put forward designs guaranteed to achieve their objects. Not all such designs have been successful and it may be said with reason, that the final solution of the problem has yet to be found". Reference to much more recent reports[6, 7] showed that the problem still could not be considered as solved.

114. The scour of a stream-bed could be taken to be a function of v^2/R (Lacey[17]), where R denoted the hydraulic mean depth, or of V^2/D (Blench[18]), and it would seem logical to expect that the scour developing off the end of a structure might well be a function of the Froude Number of the flow, $V/\sqrt{gD}$, and of the width/depth ratio. This, in fact, had proved to be the case and the relations obtained on the models tested were shown in Figs 12 and 15. The Author was not aware that this relation had been suggested before. His contention was that where the Froude Number of the flow leaving the structure was much in excess of the values indicated, then the cost of providing effective energy-dissipating devices would be high. Their effectiveness was not always easy to predict under varying conditions and hence in the absence of specific model studies, it would probably be safer and cheaper in the short or long run, to lower the apron level in order to lower the Froude Number to safer values.

115. The Author thanked Mr Wolf for his constructive contribution to the discussion. He was pleased to have his attention drawn to the fact that the results could be put into the homogeneous form suggested by Mr Wolf, but considered that they could be used more easily in the form shown in Fig. 8.

116. He was grateful for Mr Wolf's comments in § 96, which had helped to clarify his mind on the point raised. Mr Wolf's suggestion that the effect of differences in the

energy-dissipating properties of low- and high-coefficient weirs was likely to be greater in the vicinity of the crest was probably correct, but the Author had left Malaya in May 1957 and had not had the opportunity of investigating this point any further. What had been established was that the differences were not large enough to endanger the structure in any way, assuming that the latter had been designed in the manner described in the Paper.

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