CORRESPONDENCE

ON PAPERS PUBLISHED IN NOVEMBER 1938 JOURNAL.

Paper No. 5127.

"The Protection of Dams, Weirs, and Sluices against Scour." †

By Robert Valentine Burns, Ph.D., B.Sc., Assoc. M. Inst. C.E.,

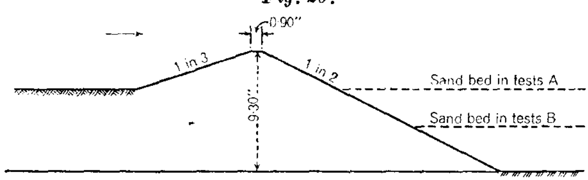
and

Assistant Professor Cedric Masey White, Ph.D., B.Sc.

Correspondence.

Mr. Jack Allen observed that, since reading the Paper, he had carried out, with the aid of students in the Whitworth Engineering Laboratory of Manchester University, a series of similar tests on a model of a weir of quite different shape. He hoped that the results obtained might be of some interest. The weir (*Fig. 20*) was tested in a glass-sided flume

Fig. 20.



5·94 inches wide and 18 feet long. Its upstream face had a slope of 1 in 3, and its downstream face a slope of 1 in 2. The bed of the channel upstream of the weir was fixed at a depth of 3·0 inches below the crest of the weir; the experiments were performed with two initial levels of the downstream bed, namely, 3·0 and 6·0 inches below the weir-crest. The material adopted for the mobile downstream bed was a Leighton Buzzard sand similar to that used by the Authors. A control-notch at the downstream end of the flume enabled tests to be made with various tailwater levels, but in beginning any experiment water was first admitted to the lower part of the flume up to the crest of the weir, in order to prevent the artificial scour otherwise produced by the first rush of water from above

† Journal Inst. C.E., vol. 10 (1938–39), p. 23 (November 1938).

the weir. Time did not permit the exploration of different bed materials or of any tests of very long duration: runs of 30 minutes were made, and the bed near the toe of the weir had by that time attained approximate stability. In the subsequent description the following notation was adopted.

Tests designated A were made with a downstream bed initially 3·0 inches below weir-crest level.

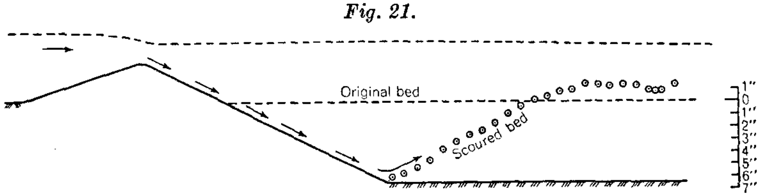
Tests designated B were made with a downstream bed initially 6·0 inches below weir-crest level.

H_1 denoted the head of water, in inches above weir-crest level, measured at a point 47·5 inches upstream of the weir-crest.

H_2 denoted the tailwater level, in inches, relative to the weir-crest level, measured 43·5 inches downstream of the weir-crest.

Test 1A: no protective sill on the downstream face of the weir; $H_1 = 2{\cdot}37$; $H_2 = 1{\cdot}32$. As shown in *Fig. 21,* the bed was scoured deeply

Fig. 21.

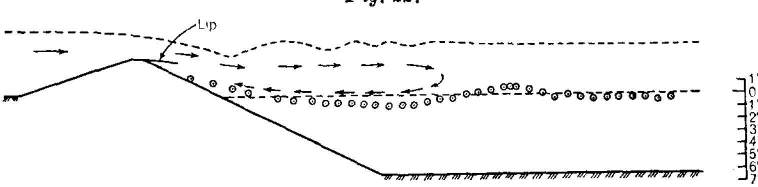


TEST 1A.

by the action of the main jet passing over the crest of the weir and clinging to its downstream face. The scoured material was deposited downstream, where the bed, some 56 inches from the weir-crest, rose as much as 2 inches.

Test 2A: as a matter of interest, the effect was tried of attaching a lip to the crest of the weir, as shown in *Fig. 22.* That prevented the effective

Fig. 22.

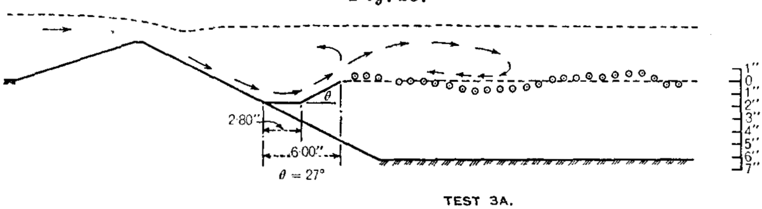


TEST 2A.

part of the stream from adhering to the weir-face, and resulted in a series of surface waves accompanied by a "reverse eddy", which actually transported sand some distance up the weir-face. The device was, however, subject to grave disadvantages: namely (*a*) it was very sensitive in action to the length and slope of the lip; (*b*) the eddy and wave system generated was essentially unstable, and could be entirely changed by a slight variation of head; and (*c*) the device could not operate successfully with lower tailwater levels or smaller discharges, because of the jet then dropping from its end, impinging on the weir-face and being directed at the sand-bed.

Test 3A: protective apron and sill as shown in *Fig. 23*; $H_1 = 2{\cdot}34$; $H_2 = 1{\cdot}42$. The arrangement was found to work well.

Fig. 23.

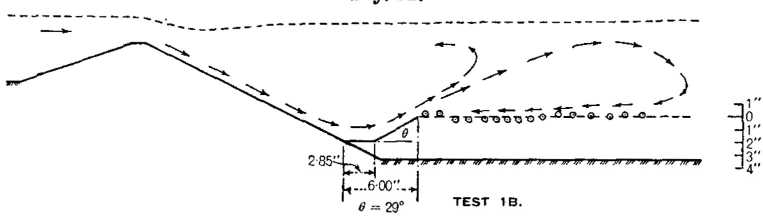


Test 4A: as in test 3A, but with $H_1 = 1{\cdot}42$ and $H_2 = 0{\cdot}38$. The sill was again satisfactory.

Test 5A: as in test 3A, but with $H_1 = 0{\cdot}57$ and $H_2 = -1{\cdot}11$. No noticeable movement of the sand-bed occurred.

Test 1B: with protective apron and sill as shown in *Fig. 24*; $H_1 = 2{\cdot}36$;

Fig. 24.



$H_2 = 1{\cdot}54$. The general bed-movement was slight, but was back towards the weir for a distance of some 20 inches downstream of the sill.

Test 2B: as in test 1B, but with $H_1 = 1{\cdot}33$ and $H_2 = 0{\cdot}31$. The sill was satisfactory, very little movement of sand-bed occurring anywhere.

Test 3B: as in test 1B, but with $H_1 = 0{\cdot}61$ and $H_2 = -0{\cdot}98$. There was scarcely any movement of the bed.

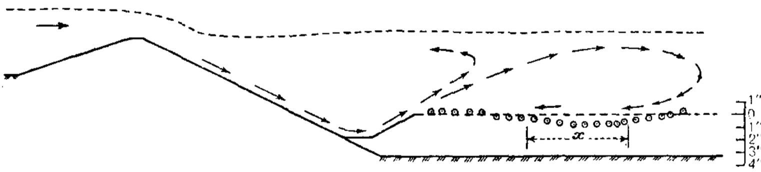
Test 4B: as in test 1B, but with $H_1 = 1{\cdot}40$ and $H_2 = -0{\cdot}73$. A slight movement of sand-bed occurred back towards the weir for a distance of some 12 inches downstream of the sill.

Test 5B: as in test 1B, but with $H_1 = 2{\cdot}38$ and $H_2 = 0{\cdot}56$. Over the length x in *Fig. 25* (p. 254), the sand-bed was from 1 to $1\frac{1}{2}$ inch higher if

17

it were measured in the centre instead of at the side of the flume. That effect was due to transverse currents.

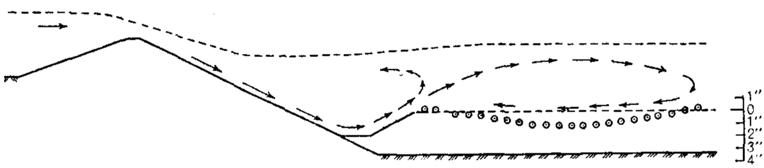
Fig. 25.



TEST 5B.

Test 6B: as in test 1B, but with $H_1 = 2{\cdot}27$ and $H_2 = -0{\cdot}75$. The effect was shown in *Fig. 26.*

Fig. 26.



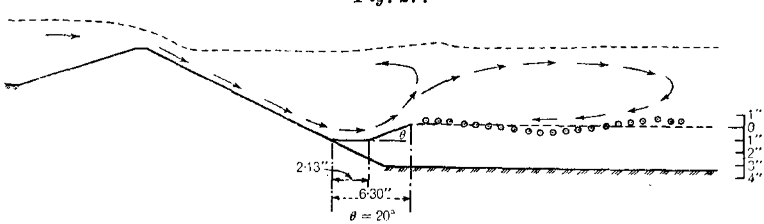
TEST 6B.

Test 7B: as in test 1B, but with $H_1 = 1{\cdot}43$ and $H_2 = -1{\cdot}74$. The movement was as in test 6B, but was not so marked.

Test 8B: as in test 1B, but with $H_1 = 0{\cdot}54$ and $H_2 = -3{\cdot}17$. No appreciable movement of sand-bed occurred.

Several experiments were next made with a different design of sill (*Fig. 27*), and with a sand-bed initially 6·0 inches below the weir-crest.

Fig. 27.



On the whole, that sill did not behave so well as the other design. An interesting phenomenon was observed when $H_1 = 2{\cdot}39$ and $H_2 = 0{\cdot}40$. For a time material was scoured from the bed and carried by the reverse current (indicated in *Fig. 27*) upstream to the sill, where it formed a bank. That bank reached such a height as to alter the regime of the flow, so that a lee eddy was produced and the bank moved downstream in the form of a ripple, leaving the end of the sill exposed. After a short time, the original eddy-system re-appeared and again carried material back to the sill, when the whole process was repeated.

To summarize, the Authors had found that a sill with slope of 20 degrees was best, with their weir, " to cope with a wide range of flows and depths." In Mr. Allen's tests on an entirely different shape of weir, an angle of 20 degrees also behaved reasonably well, although not so satisfactorily, for all depths and discharges explored, as a 27-degree slope. It was quite possible, however, that a different length of apron would have favoured the smaller angle. Incidentally, the angle of 27 degrees was very nearly that assumed by the sand-bed in test 1A when no protective device was employed.

Mr. W. E. Doran observed that *Fig. 4* (p. 29 §) showed that the final bed form in such models was independent of the grain-size of the bed-material, within the limits set by the requirements for turbulent flow on the one hand and the transportability of the bed-material by the hydraulic forces in the model on the other. With regard to the influence of grain-size on the rate of scour, however, the Authors seemed to infer rather more than the facts presented would warrant. It did not seem valid to conclude, from an experiment with only two sizes of sand, where three out of five results showed time-ratios proportional to the grain-size raised to the power 3/2, that $t/k^{3/2} =$ constant was a general law. The Authors' attempt to test the validity of that hypothesis by applying the principle to two models of different scale-ratio was ingenious, but inconclusive. To test the relationship of grain-size to rate of scour a more comprehensive series of experiments would be necessary. It was generally recognized that the theoretical time-scale could not be applied to rates of scour in models, and it would appear that further research on that matter would be very desirable.

The actual rate of scour was not usually of much importance in designing protective works, quantitative results being generally sought. It was, however, of considerable importance in tidal models where the amount of bed-movement in each tide had to correspond, at least approximately, to natural effects if reliable results were to be obtained; in such cases a method of determining grain-size would be of great use.

The Authors had presented their results as showing the effect of the angle of the sill upon its action under various tailwater depths (*Fig. 11*, p. 38 §).

It was noted that the critical angles given in *Fig. 11* had been obtained by raising or lowering a hinged flap. It was evident that in altering the angle of such a sill the height of the sill was correspondingly altered. The

§ Page numbers so marked refer to the Paper. (Journal Inst. C.E., vol. **10** (1938–39), p. 23 (November 1939).)—SEC. INST. C.E.

height of the sill, apart from its angle, had a very great influence on its effect, and therefore, since both the height and the angle were altered, the curves in *Figs. 11* and *12* (pp. 38, 39 §) did not really express the relationship between the sill-angle and the tailwater depth. What they did show was the effect of the angle of a hinged flap of length $0{\cdot}124P$, an effect which was not necessarily true of flaps of different lengths, and therefore not necessarily generally valid.

Fig. 14 (p. 40 §) gave a comparison between a "long" and a "short" sill, and it was found, for example, that when $T = 0{\cdot}543P$ the optimum angle of the shorter sill was 33 degrees and that of the longer sill 23 degrees. Under those circumstances the "long" sill would be nearly twice the height of the "short" sill, and much larger in volume. Whilst it was obvious that the angle and length determined the height of the sill, it was difficult to visualize a sill in terms of angle of slope and length of hypotenuse. It would be natural to expect that the shorter the sill the more steeply it would have to be turned up to produce the most effect. Mr. Doran suggested, therefore, that to determine the effect of different angles of sill the height should have been kept constant, whilst a further series of experiments would then have been required at constant angles and different heights.

Comparison of *Figs. 13* and *14* (p. 40 §) gave somewhat puzzling results. Although the optimum angle in *Fig. 13* was not shown, the curves in *Figs. 13* and *14* for the same length of sill appeared to differ very much in slope.

In the bottom diagram in *Figs. 10* (p. 36 §) showing the hinged sills, all three were shown as hinged about the same point, namely the end of the apron. If that method were used in obtaining the comparison then a further variable was introduced, in that the length of the apron was altered. The length of the apron in the 21-inch model was given as 4·8 inches and the lengths of the two sills used in *Fig. 14* as $0{\cdot}19P$ and $0{\cdot}071P$, or 3·99 inches and 1·49 inch respectively. The longer sill was therefore no less than 0·83 times, and the shorter sill 0·31 times, the apron-length, and, as the longer sill was found to work better at a flatter angle than the shorter one, that further accentuated the effect of the difference in the apron-length.

Possibly the Authors had investigated the influence of the sill-height also, and if so their results would be of interest.

It was stated that the results obtained could be readily applied to sluice-gates, but it was not clear how the ratios h/P and T/P could be applied to such structures.

It would be of the greatest value if a series of formulas or graphs could be obtained from which the best height and slope of sill could be obtained, once the conditions were known, but the Authors did not appear to have

§ *Ibid.*

succeeded in deducing any general laws as a result of their experiments. The various graphs shown represented the results of different experiments under different conditions, rather than an attempt to investigate separately the different variables involved by so arranging the experiments that only one variable was altered at a time. The angle and height of the sill varied simultaneously, for instance, in *Fig. 11* (p. 38 §). In *Fig. 12* (p. 39 §) the length of the sill was slightly different to that in *Fig. 11*, whilst in *Fig. 14* (p. 40 §) it was different from either. The sills in *Figs. 17* (p. 44 §) seemed to be different in height from those in other experiments. The result was that it was really impossible to arrive at any conclusion of a basic character by a comparison of the results obtained.

In *Figs. 15* (p. 42 §) a comparison was made between a Rehbock sill and a sloping sill which was varied in angle to suit the water-levels. The larger sloping sill was obviously much bigger than the Rehbock sill, and although the Authors mentioned that the smaller sill was approximately the same size as the Rehbock sill, it appeared from *Figs. 15* (particularly the top three diagrams) to be much higher than the Rehbock sill. In actual practice it was usually necessary to contend with a considerable range of water-levels, and it was interesting to note that in such cases the Authors had found a 20-degree sill to be as good as the Rehbock type. Particulars of those experiments would be of interest.

In *Figs. 17* (p. 44 §) in which three of the four sills shown appeared to be of approximately the same height, and therefore comparable, it was shown that the $26\frac{1}{2}$-degree sill failed when $T = 0{\cdot}5P$ approximately, the ratio h/P being 0·205, whilst the $12\frac{1}{2}$-degree sill gave adequate protection; yet the curve in *Fig. 12* (p. 39 §) gave the optimum angle as 25 degrees for $T = 0{\cdot}5P$ and $h/P = 0{\cdot}175$ or over. Those results appeared to be entirely conflicting. Probably the sills were of different height in the two cases, and it would be of interest to know if that were the case. If so, what were the relative heights above the apron? If that were the explanation of the difference, then the Authors' conclusion on pp. 44–45 § that "if the sill has to cope with a wide range of flows and depths the best angle seems to be 20 degrees," which apparently was based upon the experiments shown in *Figs. 17*, might be found to be no longer valid for a sill having a height different to the one at which the tests were carried out. That served to emphasize Mr. Doran's view that the Authors were not entirely correct in presenting the results of their experiments as the influence of the sill-angle on the behaviour of the sill under various conditions, and hence emphasized the danger of making general deductions from the results presented.

Mr. Doran fully agreed with the Authors regarding the importance of placing the apron at a sufficient depth below the lowest tailwater level. Scour-holes of surprising size had frequently been found below com-

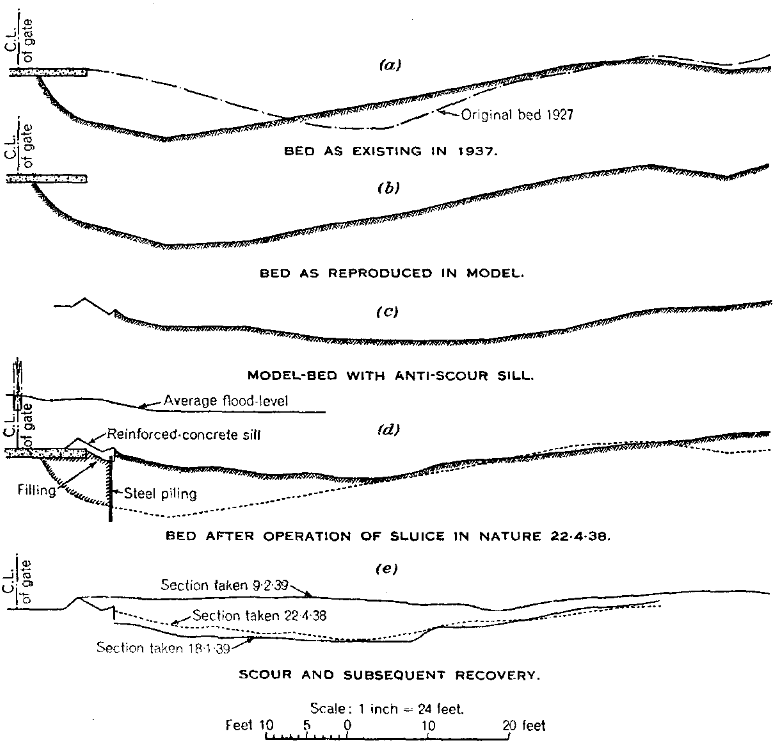
---

§ *Ibid.*

paratively small sluice-gates, due principally to the neglect of that precaution. Such cases were a difficult problem. The apron itself was nearly always undermined, and it was useless to fill in the scour-hole since, unless other measures were taken, the filling would be scoured away again.

He had carried out some experiments on a structure of that kind early in 1938. The structure was a sluice of 18 feet span, and 6 feet high. The apron was much too short, being only 8 feet 6 inches in length, and

Figs. 28.



was at too high a level. A scour-hole 9 feet deep was formed below it and it was possible for a diver to walk upright underneath the apron.

A model was constructed and the bed was modelled to the conditions existing when the structure was built. The model was then run under water-levels obtained from past records, and was found to reproduce with great accuracy the actual scour obtained in nature (*Figs. 28* (*a*) *and* (*b*)). Further experiments showed that, whilst satisfactory protection could be obtained with a triangular sill at high tailwater levels, scour occurred when the levels fell below a certain height. Consideration of the problem suggested that at the lower levels the sill was acting like a miniature weir, the water falling over its vertical face and scouring the bed.

That suggested the possibility of remedial action by extending the sill with a slope in a downstream direction, ending in a small triangular sill. That was very successful, and the secondary sill was found to prevent any scour even when the downstream level was only slightly above the top of the primary sill. The constructional work required was also very simple. The model-experiments showed that to enable the sill to work properly, streamline wing-walls would be required on either side.

The work was carried out in accordance with the indications of the model-experiments, and when it was completed a quantity of shingle from the bar formed by the erosion was dumped into the scour-hole. The sluice-gate was then opened and it was found that in a very short time the dumped material had been levelled off and pulled up towards the structure by the action of the sill. The final line of the bed agreed very closely with the result obtained in the model, as might be seen on reference to *Figs. 28* (*c*) and (*d*).

Towards the end of 1938 some workmen who wished to carry out some minor bank repairs opened the sluice and left it open at levels at which it was not intended to be used and at which model-experiments had shown that scour would take place. That action resulted in considerable scour in quite a short time. When that was discovered the bed was found to be as shown in *Figs. 28* (*e*). It was decided to wait until higher levels were available and then to operate the gate to see whether or not the sill would pull back the bed-material. The gate was left full open during the floods which occurred at the end of January, and when surveyed on the 9th February, 1939, the scour-hole was found to be completely filled in and the bed-material piled up to the top of the primary sill, as shown in *Figs. 28* (*e*). Since there was not sufficient material downstream of the sluice to fill in the scour-hole, it was evident that it had been filled in by material carried down by the river during the flood. The scour-hole was filled in as shown on the section during a period of only 10 days, some 350 cubic yards of material having been deposited during that time. The material filling the hole was sand. That result showed that it was not necessary to have filled in the hole by dumping from barges, as the sill would have done that if left to itself.

Mr. Doran mentioned that instance because the use of a double sill of that type was quite new, as far as he was aware, and because it afforded a method of dealing with existing structures where the apron had been fixed at too high a level and had become undermined in consequence, a condition very common at mills and sluices on English rivers. It also showed a very important characteristic of triangular sills, such as those described by the Authors, as compared with "energy-killing" devices such as baffle-piers; namely, what might be called the recuperative effect of the triangular sill, in being able to replace material which had been scoured out by misuse of the sluice-gate. It might happen in some cases that for some unforeseen reason the sluice might be opened at water-levels at which it was never intended to be operated, with the result that damage might be done in a few hours which it would take weeks to repair if it were not the property of the sill to produce a "piling eddy" downstream of the structure. If the river carried any appreciable amount of material in times of flood it would not be necessary in many cases to go to the expense of filling in the scour-hole, since that would be done, as in the instance just given, by the sill itself. All that was required was a suitable sill and some protective piling to keep the apron secure until the scour-hole had become filled in.

The Authors in their investigation had necessarily to confine themselves to an ideal structure discharging between the parallel walls of the flume. In actual structures, however, one of the principal difficulties which arose was with the arrangement of the structure in plan so that a gradual enlargement could be obtained, without which vertical eddies would form that might destroy completely the action of the sill. The importance of that point did not appear to be sufficiently realized by engineers. In designing a structure it should receive very careful consideration, and in running model-experiments the greatest care should be taken to ensure that the conditions of the entrance and exit of the water in relation to the structure were as nearly as possible those of the prototype. Experience with models showed how difficult it was to foresee the effect of apparently small variations between approximately similar structures, and emphasized the necessity of making a careful model-experiment with every structure before deciding upon the best height and slope of sill and its auxiliary protective works. Nothing could be more dangerous than to decide blindly upon a particular sill and to adopt it as a means of protection without full knowledge of its action under the conditions existing in the case under consideration.

Apart from the intrinsic interest of the Paper, it was of value in indicating further useful lines of investigation in connexion with anti-scour sill design.

Dr. Ing. Theodor Rehbock, of Baden-Baden, observed that the investigations of the Authors could be divided into three parts: firstly, the examination of the general rules of hydraulic-model research, especially in regard to the laws of similarity, the experimental equipment used, and the choice of the bed-material of the model; secondly, the examination of the scour downstream of a weir provided with a horizontal apron, and having end sills of different shape; and thirdly, the comparison of the results obtained with triangular sills with those of the "dentated sill" and of the "Osage stepped sill."

The first part of the Paper gave a clear summary of the most important fundamental rules of hydraulic research, and merited special attention. Dr. Rehbock fully agreed with the Author regarding the importance of using models of a size as small as possible for the tests; that was to say, of the smallest size with which reliable results could be obtained, depending on the laws of similarity. For many years he had advocated the expediency of small models on practical considerations, against the widespread opinion that large-size models were more advantageous, an opinion especially supported by American engineers, including the late Mr. John R. Freeman, the enthusiastic promotor of hydraulic research all over the world, who was of the opinion that large-size models would give better results.

He also agreed with the Authors that the stable final form of the model-bed was, within wide limits, much the same with different sizes of bed-material. The model-tests executed with sand and gravel of different diameters at Karlsruhe had repeatedly shown that to be true, as could be seen, for instance, in his contribution to the English edition of Mr. Freeman's book*. *Fig. 199* on p. 203 of that book showed such a comparison for bed-material of different sizes for the depth of scour on bridge-piers, and *Fig. 222* on p. 228 for the excavations downstream of the apron to the Ryburg-Schworstadt weir on the Upper Rhine. The conclusions arrived at from those tests agreed with those of the Authors, in that the final excavations were, contrary to expectations, rather deeper with a coarser sand than with a finer sand. The time in which the formation of the excavation was completed and the maximum depth of scour was attained was certainly longer with the coarser bed-material.

The Authors gave in Table I (p. 30 §) a series of figures which showed that with sand of 3·3 times larger diameter, the time necessary to finish the excavation was increased 6 times, and that to produce half, or any other fraction of the maximum scour-depth, the duration of the tests had also to be increased 6 times. According to those observations, therefore,

$$\propto = \frac{\text{time-relation}}{\text{grain-size relation}} = 1{\cdot}82.$$

Nearly the same value was observed at Karlsruhe with Dr. Rehbock's tests for the termination of the scour-depth at bridge-piers.

The evidence that the grain-size of the bed-material could be changed within wide limits without influencing perceptibly the definite form and the depth of the excavation was of value, since the duration and the costs of model-tests could be appreciably diminished by the choice of a finer grain of bed-material. The duration of the tests for the Ryburg-Schworstadt weir, for instance, could be diminished by one-thirty-sixth (that was to say, from 24 hours to 40 minutes), by replacing the fine gravel of 9 millimetres diameter, used in the beginning, by sand of a mean grain-diameter of 0·75 millimetre. By that modification it became possible to execute many more tests in the time available. That pro-

* "Hydraulic Laboratory Practice", edited by John R. Freeman. New York, 1929.

§ *Ibid.*

cedure was restricted by the fact that the similarity of the excavations would be lost if the mean diameter of the particles forming the model-bed were to become sensibly smaller than 0·5 millimetre.

The discharge over the 21-inch-high weir-model with varying heads, measured by the Authors and shown in *Fig. 3* (p. 28 §) agreed very well with the values of μ in Dr. Rehbock's formula for weirs with a circular-cylindrical crest *, namely

$$\mu = 0{\cdot}312 + \sqrt{0{\cdot}3 - 0{\cdot}01\left(5 - \frac{h}{R_m}\right)^2} + 0{\cdot}09\,\frac{h}{P},$$

if R_m were replaced by R_1 instead of by $\left(\frac{2R_1 \,.\, R_2}{R_1 + R_2}\right)$, as had been done by the Authors. The insertion of R_1 seemed suitable, because R_2, beginning only at the crest-line of the weir, would have no perceptible influence on the quantity of discharge.

In the second part of the Paper the Authors referred to the well-known fact that a horizontal apron without an end sill, even if it were of a considerable extent in the direction of the flow, could not prevent dangerous excavations near the end of the apron.

The Authors commented also upon the great influence of the height of the tailwater level over the apron on the scour. They showed that influence in *Figs. 9* (p. 35 §) by the measured vertical sections of the excavations produced with different heights of the tailwater above the apron. Those lines showed that a very low, as well as a very high, position of the tailwater produced deep excavations, whilst intermediate positions of the tailwater level produced much less scour, which might disappear even completely in some cases at the apron itself. It was therefore necessary to avoid too high, as well as too low, a level of the tailwater above the height of the apron. That phenomenon could only be interpreted by taking into consideration the different ways in which the flow of the water might be influenced by the difference between the height of the tailwater level and that of the apron for certain discharges.

In most cases it was impossible to change the height of the tailwater, because that depended only on the quantity of discharge, and on the form and the slope of the river-bed downstream of the weir. The height of the apron had therefore to be chosen in such a manner that the tailwater depth above the apron became neither too great nor too small. The proper choice of the height of the apron, which up to the present it had been impossible to fix accurately without model-tests, was of the greatest importance, since most accidents with weirs had been produced by a faulty position of the apron. It was not possible to consider that problem exhaustively in the present discussion, and therefore only a few

* Handbuch der Ingenieur-Wissenschaften, vol. 2 (Part 3, section 1), p. 54. Leipzig, 1912.

§ *Ibid.*

comments would be made to show how the height of the apron had to be determined.

The apron had to lie at such a height that with all possible discharges a diving water stream with a surface-roller was produced, for then the water would engender a shallow trough-shaped excavation, ending upstream near the foot of the apron. Out of such a shallow basin the water would flow calmly and equally distributed in the river-bed downstream. That most suitable, and therefore desirable, manner of flow was formed with a certain discharge on a given weir and apron only with a tailwater level lying between two fixed limiting heights.

When the tailwater level lay lower than the lesser of those two limiting heights, the water stream, which passed the apron in shooting flow, would not submerge immediately at the end of the apron in the tailwater. It was first deflected on high, forming a remarkably high standing wave that might be called a "spring-wave", at the end of which the water stream dived in a steep track to the bottom, where it formed deep excavations which reached far downstream and increased the possibility of washing away the banks to a considerable extent.

If, on the contrary, the tailwater level reached or exceeded the upper limiting height, that was to say, lay too high above the apron, the water stream, in changing from the diving flow with surface-roller to the flow with waved surface, would form—often only for a short time—a very dangerous transitional state which might be termed the "stretched flow." The "stretched flow" was formed if the water stream, although it was submerging above the apron under a surface-roller, did not reach the apron. It could not, therefore, be deflected by the apron in the horizontal direction. It was flowing rather with so flat a slope over a strongly prolonged ground roller, that it struck upon the unprotected river-bed downstream of the end of the apron. There it would produce deep excavations, which extended in most cases upstream directly to the apron in considerable depth, undermining the foundation of the apron. That form of flow seemed to Dr. Rehbock to be the most dangerous of all for a weir. Certainly it had caused the destruction of many weirs, although in most cases the real reason of the damage might not have been understood.

The Authors tried to interpret the excavations observed with their tests by the position of the water jump. That, however, seemed to be impossible, for, whether upstream or downstream from a water jump[1], formed on a horizontal bed, the water stream would not flow downwards in such a direction as was necessary to produce deep excavations. Such a downward-directed water stream occurred according to the foregoing

[1] In the footnote of p. 45 of the Paper, Dr. Rehbock's formula for the water-depth T downstream of a water jump was not given correctly. The value T had to be calculated from the depth t_0 and the velocity-head H of the shooting current upstream of the jump, the correct formula being $T = t_0(2\sqrt{H/t_0} - 0{\cdot}45)$.

declaration as a result of too high or too low a tailwater level, and the downward-directed water striking upon the unprotected river-bed seemed to be the real cause of the dangerous deep excavations downstream of a weir.

The Authors, having observed that a horizontal apron alone could not prevent dangerous excavations, were of the opinion that it was necessary to use "indirect methods of protection" of the river-bed, and suggested either energy-dissipators or flow-deflectors. Energy-dissipators, formed by a series of steps, blocks, piers, or arrows, built on the face of the weir or on the apron, had been shown to be of little advantage, and the Authors accordingly examined more thoroughly flow-deflectors in the form of sills placed at the extreme downstream end of the horizontal apron.

The sills used by the Authors were mostly of considerable size, lifting the water stream from the bed for a long distance, and creating between the river-bed and the water stream a ground roller of remarkable dimensions with an upstream-directed current above the bottom.

A heavy silting-up of the river-bed by that current was the result. It was formed by bed-material whirled up farther downstream, where the water stream struck the river-bed. At that place, and downstream of it, extensive excavations took place for a considerable distance.

The Authors did not express clearly what they had in view during their experiments, but it seemed that they wished to produce a strong building-up of the river-bed immediately downstream of the apron of the weir, since all the contour lines of the river bottom shown in *Figs. 15* and *16* (pp. 42–43 §) after tests with the specially recommended triangular end sills showed a heavy sedimentation above the height of the apron. Contrary to the opinion of the Authors, Dr. Rehbock considered such a high sedimentation of the river-bed downstream of the apron to be detrimental rather than advantageous. It should be avoided as it was not necessary for the protection of the weir and its apron, and gave rise to the destruction of the river-bed downstream of the weir. A well-constructed weir should calm the water flow and should introduce it, equally distributed, in a short stream-length in the river-bed adjacent, and should then re-create the normal flow as soon as possible; by doing so it would reduce the length of bank which had to be protected.

To satisfy that requirement, it was necessary to create close to the apron a shallow basin extending below the height of the apron, but not to raise up the river-bed above the height of the apron, since an increase in height would only shift the excavation downstream, and would produce an increased slope of the river-bed below, on which shooting flow might arise; that would lead to the formation of washed-out channels through which the discharge was locally increased, thus preventing the equal distribution of the water in the river-bed.

---

§ *Ibid.*

Most of the sills examined by the Authors were simple triangular sills whose vertical side was directed downstream. The Authors, attaching special value to the determination of the best angle of the inclined surface, had come to the conclusion that the best slope varied, within wide limits, with the quantity of the discharge and with the tail-water level, even with the same weir. The Authors recommended a moderate slope-angle of 20 degrees, that was to say, a slope of 1 in 2·75, if the quantity of discharge and the tailwater depth varied considerably, as was generally the case with weirs. In 1921 Dr. Rehbock had made tests with a view to finding, by means of such triangular sills, an arrangement which would avoid dangerous excavations. For various reasons he had soon to abandon that form of sill, amongst them being the fact that the same triangular sill could not be adapted satisfactorily to changing discharges; further, he had succeeded meanwhile in finding the dentated sill, which showed itself superior to other known sills in various ways. Concerning the comparison of the triangular sill with the dentated sill in the third part of the Paper, he wished to point out that in none of the five sections of *Figs. 15* (p. 42 §), measured on the apron with a dentated sill by the Authors, was any scour observed near the apron, and that in none of the sections was the slope-line of the excavation inclined more than 1 in 3.

Those facts showed that with respect to the protection of the apron the dentated sill had met all requirements, as had also been the case with the triangular sill. In the tests with a dentated sill it should have been possible even to have reduced the excavation somewhat more, thereby shortening the length of scour by reducing the height h_z of the dentated sill; that height should, according to his formula of 1931, be not more than:

$$h_z = 0{\cdot}08h^{2/3} \, . \, P^{1/3} \quad . \; . \; . \; . \; . \; . \; . \; . \quad \text{(i)}$$

With the head $h = 0{\cdot}175P$, which had been adopted in the Authors' tests, the height of the dentated sill had to be, according to that formula, not more than $h = 0{\cdot}025P$, or 13 per cent. and 36 per cent. respectively of the height of the two triangular sills used by the Authors in their comparison with the dentated sill shown in *Figs. 15* (p. 42 §), which had heights of $0{\cdot}19P$ and $0{\cdot}07P$ respectively. According to (i), with the head $h = 0{\cdot}175P$ and with a weir-height P of 40 feet the dentated sill should be only 1 foot high, and with a weir-height of 80 feet it should be only 2 feet high. That small height of the dentated sill reduced the quantity of material necessary for the construction of the two triangular sills used by the Authors to 1·2 and 8·8 per cent., and diminished the danger of their being struck by floating trunks passing over the weir.

The Authors on p. 36 § stated that "the problem [of protection] finally resolved itself into one of finding the smallest possible apron and deflector

§ *Ibid.*

compatible with effective protection, the aim being to minimize both first cost and maintenance."

It seemed to him that the dentated sill, giving effective protection and reducing the material necessary for the flow-deflector to 1/83 or 1/11 in the two sizes of that necessary for the triangular sill (depending on which sill was used), should be given preference, the apron requiring the same quantity of material with the different sills.

Further important tasks of the end sill of an apron were the protection of the river-banks by calming the water, after the fall over the weir, as quickly as possible; the leading-off of the shingle and floating material without retardation; and the prevention of low-water excavations, which might be produced on account of insufficient tailwater depth during times of low water, with sills having a vertical downstream face, as had the triangular sill. None of those requirements, all of which were satisfied by the dentated sill, was mentioned in the Paper, whereas the Authors asserted that a triangular sill with an angle of 20 degrees, when tested, was "as good as Rehbock's, whilst it had the advantage of being free from constructional irregularities likely to require maintenance." To that statement Dr. Rehbock replied that the dentated sill was actually of very simple construction and of a shape which all requirements conformed excellently to. Even the hardest shingle in torrents would do no damage to the teeth if they were properly constructed.

That had been confirmed again, recently, by the experience gained on the weir at Pizançon, on the Isère torrent in the French Alps, which had a maximum discharge of 53,000 cusecs, and a fall of 46·5 feet. That weir, completed in 1931, had a dentated granite sill 2 feet high. Careful examination of the teeth after 7 years' use showed that the cross section had only been reduced by wear to the extent of 1/750 part by the very hard shingle of quartzite, granite, and gneiss carried by the Isère. Similar observations had been made on other weirs with dentated sills, even in large mountain rivers. He had not been advised, up to the present, that any dentated sill had had to be repaired or renewed. He could not, therefore, accept as being fair the opinion of the Authors that the dentated sill required special maintenance. From the practical experience of the last 15 years, during which period hundreds of dentated sills had been installed in more than thirty different countries, including some on small weirs in England, it had been proved that such maintenance was not necessary.

Many thousands of tests had been carried out at Karlsruhe with dentated sills on hundreds of weirs of different shapes, the observed results on many of the models used having been compared later with those obtained on the actual weirs when they were constructed. Apart from the work in the laboratory at Karlsruhe, other experimenters had repeatedly tried to find some other arrangement superior, or at least equal, in efficiency to the dentated sill, but without success. Although there were more weirs and dams in British India than in any other country, it was surprising that it was one of the few countries where the dentated sill was not used. That might be because the comparative model-tests with dentated sills, which for several years had been carried out in the Punjab Irrigation Research Institute in Lahore, had not been performed correctly; the dentated sill had not been placed in the correct spot near the unprotected river-bed, but at a distance of 60 feet upstream from the end of a layer of concrete blocks forming the downstream part of the apron, a site where it could be of no real use. The results were therefore unsatisfactory, but they had been distributed throughout India by the official publications of the Central Board of Irrigation, and also by the Reports of the Punjab Engineering Congress in Lahore. The publication of those incorrect results had undoubtedly prevented Indian engineers from adopting, and even from making trials with, the dentated sill. All Dr. Rehbock's attempts to correct the unfavourable effect of those incorrect experiments, by carrying out model-tests at Karlsruhe for Indian weirs—for example, for the Marala weir reconstruction—had failed, probably because many Indian engineers were unaware of the criticisms that he had made of the tests in India. The damage caused by not using dentated sills was bound to be considerable, in view of the losses calculated on some single weirs for which special inquiries had been made. For example, at the Marala weir the expense incurred in lowering a layer of concrete blocks, 60 feet broad by 4,000 feet long, through a distance of 4 feet, could have been avoided by the installation of dentated sills, as his model-tests had clearly shown.

He could not discuss so completely the comparison made by the Authors between triangular sill and the Osage sill, because the latter was not sufficiently well known to him. Since the Osage sill was merely a triangular sill with low steps, the effects of the two sills could not be very different. Nevertheless, the scour-lines observed by the Authors showed that the Osage sill gave better results in the tests, as it did not produce the excessive height of sedimentation downstream of the apron that was created by the triangular sill. The Osage sill, however, as it was continuous like the simple triangular sill, would not exert a beneficial influence on the river-bed downstream of the apron, as did the dentated sill. A continuous sill could not be adapted so well as an interrupted sill, to widely different discharges, and, having a high vertical fall downstream, it produced low-water excavations immediately beyond the apron; in some cases that would necessitate a secondary apron if the sill were high.

Finally, the fact might be stressed that the Authors' tests had been restricted to two-dimensional flow arising on weirs with an equally divided discharge over the whole length of the weir, such as would arise in the case of a fixed weir without a spillway. The tests took no account of three-dimensional flow over fixed weirs with spillways, and through sluice-gates in dams; in such cases cross currents, produced by the unequal distribution of the discharge, might appear, and might have an important influence on scour.

The Paper contained valuable general remarks on the fundamental laws of hydraulic research, and the results of carefully executed model-tests, but the conclusions drawn from the tests carried out seemed to Dr. Rehbock to be erroneous, and did not agree with his experience, gained on observations of actual structures and on models. He was afraid that the deductions derived from the Authors' tests would not serve to dissipate the want of confidence in the value of the dentated sill that had been created in the minds of the British engineers through the wrongly-carried-out model-tests at Lahore. That was a serious matter in view of the fact that the dentated sill had proved its value all over the world. The triangular sill, the predecessor of the dentated sill in his experiments, could not be regarded as being of the same value.

The principal difference between the Authors' opinion and his own seemed to lie in the supposition of the Authors that it was desirable to obtain as high a level as possible of the river-bed immediately downstream of the apron, whereas in his opinion the best solution was to form a shallow basin downstream of the apron, ending upstream immediately at the apron. In that basin, in most cases excavated by the water itself, a ground roller had to be formed with an upstream-directed flow, just above the bottom, which prevented the particles of the river bed immediately downstream of the apron from being carried away downstream. In that case, no scour could occur immediately at the end of the apron, and thereby endanger the apron and even the weir, as well as increase the possibility of piping.

The Authors, in reply, wrote that Mr. Allen's experiments, when compared with their own, showed that considerable change in the downstream slope of the weir-face had but little effect on the action at the toe. A few feeler experiments had also led them to that conclusion. Among other things, the combined thickness of the overflowing jet and associated mixing zone just upstream from the sill influenced its action. It was the angle of slope of the sill combined with the length of the slope in the direction of flow which had the greatest effect on the protective value of the sloping sill. The Authors' experiments had disclosed the danger-region *D* in *Fig. 11* (p. 38 §), and their suggested 20-degree sill-slope was a compromise to avoid the danger-region and other troubles, and was less than what at first appeared to be the optimum angle. They thought that those considerations would together account for a little more than the extra 7 degrees mentioned by Mr. Allen. They did not think that the shape of any toe should be based on the shape of an unprotected bed, for in their own experiments with completely exposed beds, they had found much steeper slopes than that mentioned by Mr. Allen.

§ *Ibid.*

The natural bed adjusted itself until the drag was approximately uniform, whereas if an artificial apron and sill were so designed there was risk of premature breakaway when conditions changed. It seemed best to design, if possible, for increasing drag, right up to the point where breakaway was desired, as there was then less risk of negative drag near the toe.

As Mr. Doran pointed out, the rate of scour relation should on no account be regarded as an established generalization applicable to all kinds of bed-movement problem. It did not, for example, apply to wave-action on a sea-shore, for there an entirely different motion occurred, with the paradoxical result that heavy shingle was moved more rapidly than sand. It was, however, interesting to hear that Dr. Rehbock had observed that the rate of scour near bridge-piers varied approximately in the same manner as with the Authors' weirs. Perhaps in the near future it would be possible to explain such observations by reference to existing theories of turbulent suspension.

The Authors wished to point out that the series of bed formations in the various Figures in the Paper were selected from many hundreds to illustrate either particular sequences of actions or particular characteristics of certain sills, and although quite typical they were not the main experiments on which *Figs. 11* to *14* (pp. 38 § *et seq.*) were based. Some differences were therefore to be expected, but that to which Mr. Doran referred was not an experimental inconsistency but was due to comparing sills which were of different lengths. Mr. Doran should compare *Figs. 17* (p. 44 §), not with *Fig. 12*, but with *Fig. 14*, which concerned a rather similar length of sill; he would then find satisfactory agreement.

The Authors had certainly varied more than one variable at once, but Mr. Doran's criticism that they should not have done so seemed without foundation. Whenever the effect of change of geometrical shape was being investigated it was, in general, fundamentally impossible to change one dimension only. Further, Mr. Doran could not avoid the difficulty by using rectangular co-ordinates in place of the polar ones used by the Authors. The height of the sill could certainly be used as one of the variables, but the Authors avoided its use as they had found that it was at times misleading. The height was readily found from the length and angle of the sill, and those two variables had the advantage that they drew attention to the immediate purpose of the sill, which was to deflect the stream through a certain angle, and they also enabled a very wide range of complicated phenomena to be co-ordinated and condensed into the simple diagrams, *Figs. 11* to *14* (pp. 38 § *et seq.*). Dr. Rehbock's criticism that the depth of scour was a poor measure of the performance of a sill was no doubt true, but the Authors viewed the matter from a different standpoint. They also had found that a moderate depth of scour greatly assisted the action of most sills, but they considered that a sill

§ *Ibid.*

which required such assistance had less margin of safety than one which would act without it. If that were so, then their use of the depth of scour seemed justified, particularly when, as in the present case, it was considered in relation to its distance away.

The Authors would be very sorry indeed if any remarks of theirs seemed to disparage the dentated sill. It was one of the finest examples of successful scientific design which it was possible to find. In the light of Dr. Rehbock's experience they unreservedly withdrew the criticism implied in their remark "as good as Rehbock's, whilst . . . free from constructional irregularities likely to require maintenance." In writing that, they had had in mind the point that the simpler the form the better. In India the dentated sill had had a bad Press, due to failure to appreciate what its purpose was. At Lahore experiments had previously been made with dissipators, and from the account of the experiments it seemed clear that an attempt had been made to use the dentated sill also as a dissipator, whereas, of course, it was essentially a deflector, and a very successful one.

In comparing the relative sizes of sills, possibly Dr. Rehbock had misread S as the height of the sill, whereas it was actually the sloping length. The main comparisons between the dentated sill and the simple sloping sill had been made with sills approximately equal in size, and a whole series of tests had been made to examine that very point. Some of the other apparently greater sills did not involve additional volume, for they represented an apron shaped in a particular way, and were not to be regarded as superstructures added to an existing flat apron. That point of view was illustrated by *Fig. 18* (facing p. 29 §), which showed an early attempt to design the sill, apron, and weir as a single entity. It was interesting to hear that Dr. Rehbock had tried and discarded triangular sills in 1921, but it should not be forgotten that at that date the causes of boundary-layer breakaway were understood only by a few specialists in aerodynamics, and the subject was entirely unknown to ordinary engineers. All the more credit was due to Dr. Rehbock for his success at that date, but it followed that his finding with regard to triangular sills was correspondingly less conclusive. To-day, within certain ranges, it did seem possible to obtain the results of a dentated sill by using a simpler and more compact design on the lines of *Fig. 18*, although there were cases in which the dentated sill undoubtedly had the advantage, particularly when the apron was already in existence at too high a level.

The Authors thought that moderate scour had very little influence upon the risk of piping. The under-leakage was mainly controlled by the regions in which the streamlines were most congested, and the small reduction in the length of leakage-path with any bed-configuration that they had accepted as safe would only cause a minute increase in leakage. On the other hand, scour very close to the toe was dangerous, for not

§ *Ibid.*

only did it leave the structure locally unsupported, but it might also remove one of the regions of congestion, and so cause piping.

A very dangerous type of motion occurred when the submerged jet remained separated from the weir and apron by a large bottom roller. That only occurred under very critical conditions, and might easily be missed if the tests with a model were insufficiently exhaustive. The Authors had made many hundreds of experiments, and yet had not found such motion until one day it was disclosed by the small model used for the photograph, *Fig. 18* (facing p. 29 §). Once aware of it, they had reproduced it fairly easily in the larger model. They thanked Dr. Rehbock for calling attention to that danger; perhaps they ought to have done so themselves, but they feared making their Paper too long. For the same reason they had restricted the descrption to two-dimensional models, but, with Mr. Doran and Dr. Rehbock, they would emphasize that further important difficulties were met when the complete three-dimensional model was tested.

Paper No. 5157.

"An Aerial Survey of the Estuary of the River Dee, employing a Simple Method of Rectifying Oblique Photographs." †

By James Louis Matheson, M.Sc., Assoc. M. Inst. C.E.

Correspondence.

Mr. Jack Allen pointed out that the value and ingenuity of the method devised by the Author to produce a map from the given photographs of the Dee estuary were especially apparent after the abortive attempts made by other methods, such as that of projecting the photographs upon an inclined screen by means of a lantern. Mr. Allen and two research students had used the Author's method to make a plan from another set of photographs of the Dee estuary, taken in September, 1938. Their experience had confirmed the conclusions set out in the Paper regarding the distance of the eyepiece from the lantern slide, the degree of accuracy obtainable, and the desirability of well-defined control points. It was important to realize that in plotting the final map as a weighted average of projections from different photographs, the accuracy might be improved by continual reference to the photographs and the use of the principle that collinear points on them were bound to be collinear also in the plan. Certainly the method would not yield the accuracy of more elaborate

§ *Ibid.*

† Journal Inst. C.E., vol. 10 (1938–39), p. 47 (November 1938).