MODEL STUDIES OF SCOUR AROUND BRIDGE PIERS AND ABUTMENTS—SECOND PROGESS REPORT

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SYNOPSIS

The Iowa Institute of Hydraulic Research is engaged in a laboratory investigation of four phases of scour at bridges: (1) geometry of piers and abutments, (2) hydraulic characteristics, (3) sediment characteristics, and (4) geometry of channel cross-section and alignment. A previous report, given at the 30th Annual Meeting of the Highway Research Board, presented results of the first year's investigation on the effect of the geometry of representative Iowa designs of piers and abutments.

During the past year the more fundamental aspects of the problem have received special attention in an investigation of the effect of velocity and depth of flow on the depth of scour—the second phase of the program. Work on the first phase has been continued in a search for shapes and devices which would minimize scour. Although possible improvements are indicated by the latter study, their practicability is dependent upon the results of the other phases of the investigation and upon the structural requirements of pier design.

Study of Phase 2 indicates equilibrium depth of scour is primarily dependent on the depth of flow and that velocity has little influence on equilibrium conditions. The instantaneous rate of scour, however, is greatly influenced by the velocity, and scour depths in excess of the equilibrium condition can be attained under unsteady flow conditions. A flood, of course, is a state of unsteady flow, and an alluvial stream will have a tendency to degrade during the rising stage. The lowering of the bed results in a variable level to which the scour depth, as determined by these laboratory tests, must be referred. Further investigation is necessary, however, to determine whether the excess depth or the equilibrium depth of scour will obtain during the slowly varied flow of floods.

UNDER THE SPONSORSHIP of the Iowa State Highway Commission and the Bureau of Public Roads, the Iowa Institute of Hydrauilc Research is engaged in a laboratory investigation of the bridge-pier scour problem. On the basis of the variables which influence the scour depth and the controls which are possible in the laboratory, the experimental program has been divided into four phases: (1) geometry of piers and abutments, (2) stream-flow characteristics, (3) sediment characteristics, and (4) geometry of channel cross-section and alignment. The technique which is being employed is that of a generalized model study.

At the thirtieth Annual Meeting of the Highway Research Board a paper (Research Report No. 13-B, 1951) was presented on the results of the first year's investigation of Phase 1. During this initial period, representative Iowa designs of piers and abutments were tested for comparative tendency toward scour. Besides the detailed information on scour patterns, which permitted several practical recommendations to be made, a general understanding of the scour process was obtained from the study. Two basically different methods of reducing scour were evident. The relationship between the scour depth and the drag coefficient of the pier shape in two-dimensional flow indicated that a streamlined shape would be desirable, since this would minimize the erosive action of the spiral roller within the scour hole. Since the active area of entrainment was the bottom of the scour hole, protective devices which would impede erosion at the bottom without shifting the area of attack should also reduce the depth of scour.

During the past year the study of pier geometry was continued by D. E. Schneible, of the Bureau of Public Roads, as an M.S. thesis. Shapes which would be hydraulically more efficient were sought, and various devices which would inhibit the action of the roller were tested. The pertinent results are summarized in the following section.

The primary effort of the past year, however,

has been devoted to Phase 2, a study of the more fundamental aspects of the scour phenomenon: the effect of velocity and depth of flow. This phase of the investigation is described in detail in a subsequent section.

PIER GEOMETRY

Further tests on the effect of pier shape were conducted in the same flumes and by means of the same techniques described in the previous report. In fact, the scour characteristics of the simple cylindrical shaft presented therein were used as the basis of comparison.

The effectiveness of streamlining piers which are aligned with the flow is shown in Table 1. It will be seen that appreciable reduction in scour depth can be obtained in comparison to that caused by a single round shaft, regardless of whether the comparison is based on equal width or equal cross-sectional area of shaft. If these same piers are skewed to the direction of flow, however, their hydraulic efficiency is decreased. In fact, if the angle of skew is too great, they can no longer be considered streamlined. In Table 2 the effect on the relative scour of a 30-deg. skew is shown.

Several difficulties are attendant upon any comparison such as this of the effectiveness of different pier shapes. From the viewpoint of hydraulic efficiency, the angle between the pier and the approaching flow is of major importance. The only shape that can be considered efficient for all angles (up to 90 deg.) is the single round shaft. Moreover, the angle of approach will vary with the river stage and with changes in the river channel and the valley floodplain upstream. A valid comparison must assess these other factors, which have not as yet been studied.

From the standpoint of design it is not sufficient to compare hydraulic efficiency alone, for in the final analysis the pier shape must be selected on the basis of the minimum cost required to achieve the desired results. First of all, it is evident that a clear formulation of the structural strength and stability requirements of piers is needed. Secondly, the construction methods and costs of meeting these requirements with minimum sections must then be considered. These factors, not simply width or cross-sectional area, should be the ultimate basis for the comparison of hydraulic efficiency.

In addition to streamlining the pier itself, scour may be inhibited by the addition of structural devices which either disrupt the roller action or form a protective surface between the roller and the bed. If placed at the bed level the lateral extent of such a surface must be extremely great; if below the bed level, the

TABLE 1
COMPARISON OF SCOUR DEPTHS AROUND SINGLE ROUND SHAFT AND STREAMLINED PIERS ALIGNED WITH FLOW

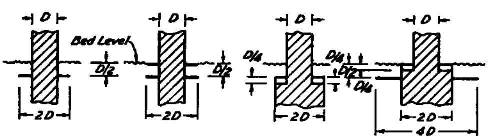
Shape	Length-Width Ratio	Reduction for Equal Width	Reduction for Equal Area
		percent	*percent*
Rounded	2:1	0	+23
	3:1	+4	+35
Elliptical	2:1	+11	+30
	3:1	+18	+42
Lenticular	2:1	+11	+25
	3:1	+26	+45

TABLE 2
COMPARISON OF SCOUR DEPTHS AROUND SINGLE ROUND SHAFT AND STREAMLINED PIERS AT 30-DEG. ANGLE OF APPROACH

Shape	Length-Width Ratio	Reduction for Equal Width	Reduction for Equal Area
		percent	*percent*
Rounded	2:1	−15	+11
	3:1	−22	+17
Elliptical	2:1	−8	+9
	3:1	−22	+13
Lenticular	2:1	−8	+6
	3:1	−22	+8

Note: Negative reduction indicates an increase in scour depth.

TABLE 3
REDUCTION OF SCOUR DEPTH AROUND SINGLE ROUND SHAFT BY ARRESTORS
Arrestor Type



+41 +52 +52 +48
Percent Reduction

lateral extent must be sufficient to prevent undercutting. The reduction in scour depth which could be accomplished in the laboratory with the best devices tested is shown in Table 3.

These tests indicate that, with properly proportioned and positioned arrestors, it is possible to reduce the scour depth by approximately one half. However, other tests show that, if the arrestors are not properly proportioned and positioned, the scour depth may not be reduced at all. It is readily apparent that the design of the arrestors in particular their proper location in the vertical, is dependent on the geometry of the unarrested scour hole, which is a function not only of the pier geometry but also of the variables still being studied in the other phases of the investigation.

VELOCITY AND DEPTH OF FLOW

The flume built for the study of stream-flow characteristics (Fig. 1) differed from the flumes used in the first phase only in the inclusion of a sand trap and scale at the lower end of the flume, so that the rate of transport could be measured, and a sand elevator at the upstream end, whereby sand could be added at a known rate. Whereas in the studies of geometry the shapes were varied and all other factors held constant (velocity and depth of flow and sediment size), in this investigation a single pier (Fig. 2) was used and the velocity and the depth of flow were varied independently. The sand used was the same as in the previous study.

A measure of the elevation of the sand surface at the upstream shaft was obtained with-

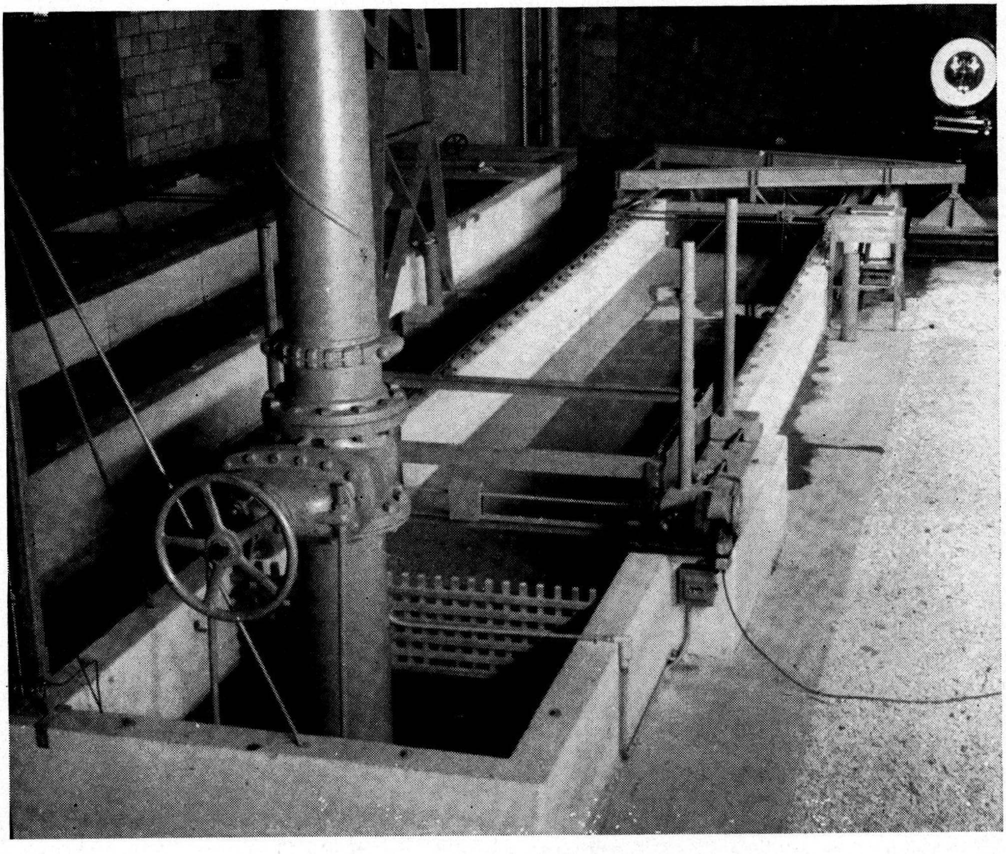


Figure 1. Flume for study of stream-flow characteristics.

out interference with the scour action by means of an instrument utilizing the difference in electrical resistivity between water and sand-water mixtures. As the scour hole deepened, successive electrodes in the front face of the pier were exposed. Whether the sand still covered a given electrode could be detected by checking the current flowing between it and

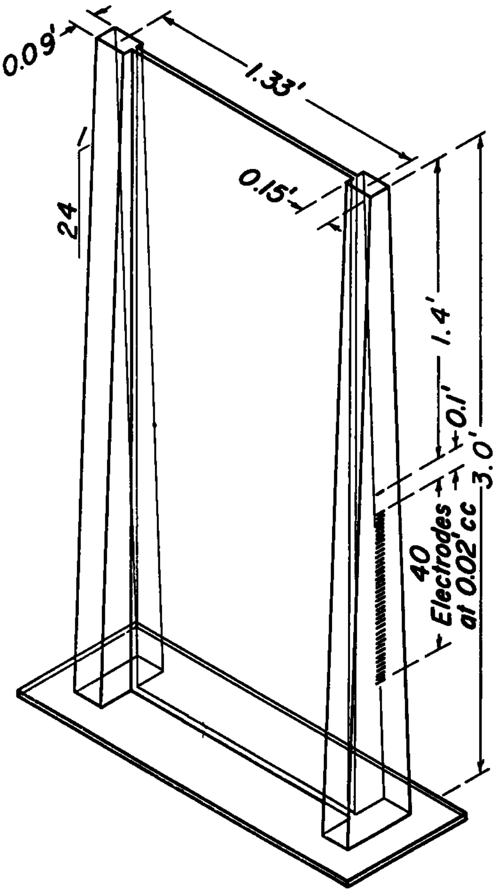
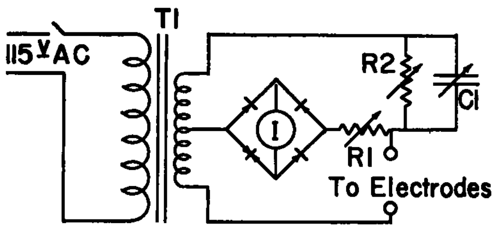


Figure 2. Model pier.

the reference electrode with the circuit shown in Figure 3. Switching between electrodes permitted the measurement of the sand ėlevation to an accuracy of 0.02 ft, the spacing of the electrodes.

The experimental technique employed was the same for all runs. Starting with a level sand bed and the pier in place, the desired rate of discharge was established with a large depth. The desired depth of flow was then established by lowering the tailgate. The sand trapped at the lower end of the flume was weighed continuously and the elevator at the upper end was raised at a corresponding rate to maintain the sand bed in the flume. The scour depth was checked at 30-second intervals. It was found that an equilibrium bed configuration would eventually be established by the flow, and that the transport rate and the scour depth would then fluctuate about constant mean values. Since the dune movement was detectable in the trapping rate and since the scour depth was influenced by the dune movement and by random turbulent fluctuations, average values had to be determined over a considerable period of time.



T1 - 20 to 1 transformer
I - 0 to 50 microamperes
R1 - 50,000 ohms max.
R2 - 10,000 ohms max.
C1 - 1 microfarad max.

Figure 3. Circuit diagram.

The effect of velocity and depth of flow on the equilibrium depth of scour is summarized in Figure 4. These results indicate quite forcibly that the depth of flow has a primary influence on the scour depth under equilibrium conditions, and that the velocity has very little effect. The soundness of these conclusions is apparent from a consideration of scour as a particular aspect of the general phenomenon of sediment transportation. The active agent of transport in the unobstructed portion of the flume is the flow at the grain level, *i.e.*, in the immediate vicinity of the moving particle on the bed. The velocity at this level is a function of the mean velocity and the depth of flow. The agent of transport in the scour hole is the roller, the peripheral velocity of which is a function of the mean velocity and the size of the scour hole. At least as a first approxima-

tion, the rate of transport in the scour hole should bear the same relation to the mean velocity as does the rate of transport in the unobstructed portion of the flume. Once these rates are in balance, the depth of scour should not change with a change in the velocity, since the rates would then tend to change by equal amounts. In other words, the velocity pattern and, consequently, the equilibrium scour pattern should be independent of the velocity magnitude. This would seem to be the case

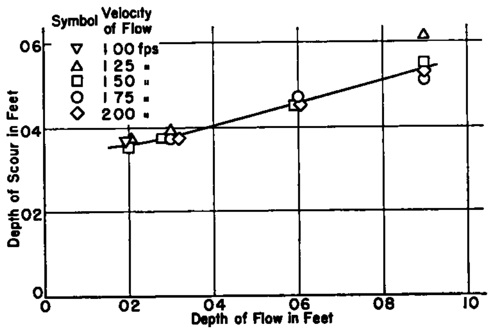


Figure 4. Depth of scour versus depth of flow.

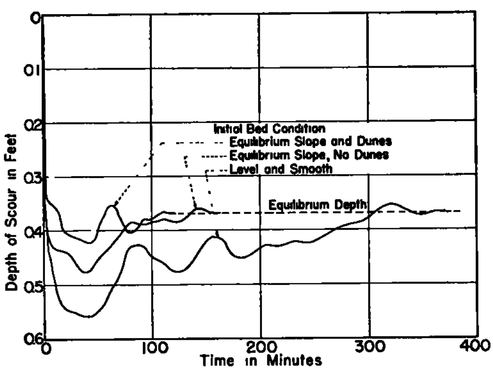


Figure 5. Depth of scour versus time.

within the degree of precision of the measurements.

The same line of reasoning explains, at least qualitatively, the effect of depth of flow on the equilibrium depth of scour. The velocity at the grain level is, according to the logarithmic velocity distribution, inversely proportional to the logarithm of the depth. Consequently, since the velocity of the roller is proportional to the mean velocity and the size of the scour hole, the depth of scour must increase with increasing depth of flow. That such a connection exists is shown by the experimental data, although the range and precision of the measurements are insufficient to define the relationship exactly.

The history of the scour hole, before equilibrium depth is attained, is dependent upon the initial bed conditions in the flume. Figure 5 shows the variation in the development of scour for three such conditions. For the initially level bed, the depth of the scour hole shortly after the beginning of the run exceeded the equilibrium depth considerably, as may be seen from the lowest curve. Visual observation of the flow indicated that the scour hole refilled only after a foreset dune moving from the elevator had reached the scour hole, thus establishing the required slope. After equilibrium had been established, the dunes were smoothed, without changing the bed slope, and the scour hole was filled. This resulted in a smaller but still appreciable excess depth of scour, shown in the middle graph of Figure 5, until the dune conditions had been reestablished. Finally, the bed was left in its equilibrium condition but the scour hole was again filled. This caused a variation in depth little greater than that occurring during equilibrium conditions, as seen from the upper curve.

The excess depth shown by the lowest curve on Figure 5 is partly the result of degradation of the bed before the supply of sediment equalled the rate of sediment transport. As indicated by the middle curve, however, excess depth is apparently also caused by a lag in the rate of transport behind the transport capacity of the flow, since under conditions of proper slope no further degradation would occur. Part of the excess depth seems then to result from the lag caused by need for the development of a certain dune form corresponding to the transport capacity of the flow.

The importance of the excess depth of scour during transport establishment is uncertain. It is well known, of course, that rivers flowing in alluvial materials have a tendency to degrade their beds in flood time, and this has the effect of lowering the reference plane from which scour depths should be measured. The influence of the lag between rate of and capacity for transport depends upon the time interval required to change bed conditions to match the changing flow conditions during floods. Since this time interval is as yet unknown, no

estimate can be made of the role played by excess depth in full-scale scour phenomena.

CONCLUSIONS

Although no specific shape can as yet be recommended, the general principles which will govern the design of piers for minimum scour are becoming evident. The primary criterion is that the pier should present the minimum flow obstruction. The minimum flow obstruction may be approached both by streamlining the shape and by using the smallest pier-size structurally reliable. This also implies the careful alignment of solid or webbed piers with the flow. The possibility of inhibiting scour with arrestors such as described is dependent on the designer's ability to predict the scour depth with considerable certainty. However, their use may be justified if only as a safety device. The course of future studies on shape will depend partly on the results of the other phases of the laboratory investigation and partly on information on the structural and constructional requirements of piers.

The laboratory investigation of the second phase of the program has revealed that for any pier in steady flow there is an equilibrium depth of scour which increases with increasing depth of flow but is not affected appreciably by a change in velocity. Under unsteady flow conditions, however, excess depths may be attained, because of an apparent lag in the establishment of transport equilibrium. This study is being repeated with an improved, recording version of the scour meter and a coarser sand. The range of the investigation of the second phase will thereby be extended and the study of the third phase, sediment characteristics, initiated. The recording feature of the scour meter will also be employed in exploratory investigations of unsteady flow conditions.

STRUCTURAL BEHAVIOR OF HEAVY-DUTY-CONCRETE AIRFIELD PAVEMENTS

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SYNOPSIS

THE CORPS OF ENGINEERS test program of full-scale concrete pavements, described initially in the 1944 Highway Research Board PROCEEDINGS (*4*), is brought up to date in this paper. Accelerated traffic tests have been completed on two full-scale test pavements. The traffic loadings applied were 150,000 lb. with a single wheel and with a four-wheel or twin-tandem-gear configuration. In the case of the single-wheel loading, the test pavement officially designated as Lockbourne No. 2 Experimental Mat is described in the referenced paper, and only limited results of these tests are given in this paper. A complete description of the test pavements for the multiple or twin-tandem-wheel loading is presented. The test results given include the crack-pattern development on these pavements, as well as strain and deflection measurements at selected intervals throughout the traffic loading. This latter is officially designated as Lockbourne No. 2 Modification, Multiple-Wheel Study. Comparative strains produced in a 20-in. thick pavement are given for the single and multiple loadings. Finally, results of all accelerated traffic tests obtained throughout the program are summarized on a chart showing tentatively the percent of design thickness required for a given number of load repetitions.

• THE TEST PROGRAM up to 1944 has been reviewed by Philippe (*4*). This review carries through the design and construction of the Lockbourne No. 2 Experimental Mat, which was completed in December 1944. The accelerated traffic tests of these test pavements under the 150,000-lb. single-wheel traffic were completed in January 1948. About the time these tests were well under way, in December 1945, the Air Force changed to a multiple-