PROGRESS REPORT OF MODEL STUDIES OF SCOUR AROUND BRIDGE PIERS AND ABUTMENTS

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SYNOPSIS

An estimate of the probable depth of scour around piers and abutments is necessary in the safe as well as economical design of a bridge structure. The danger of underestimating the scour depth is evidenced by the too frequent failure of bridge foundations during floods. On the other hand, a bridge which withstands all floods is not necessarily well designed, since it may be oversafe and therefore too costly. At present the only design criterion is experience, organizational or individual, which can hardly encompass all the variables in this highly involved problem. In fact, the complexity is so great that not even an approximate solution can be obtained except by first isolating the effect of each basic factor. Such arbitrary control of the phenomenon can only be achieved in the laboratory. Moreover, the technique of model studies is the only method of attack which will provide the desired relationships between the pertinent variables. The formulation of the final design criteria, however, will ultimately depend on field measurements, correlated and systematized by the experimental relationships obtained in the laboratory.

Under the sponsorship of the Iowa State Highway Commission and the Bureau of Public Roads, the Iowa Institute of Hydraulic Research has undertaken a comprehensive experimental investigation of the bridge-scour problem. The program has been divided into four phases on the basis of the variables to be studied: (1) Geometry of piers and abutments; (2) Hydraulic characteristics of the stream, primarily the velocity and depth of flow; (3) Sediment characteristics; (4) Geometry of channel cross section and alignment.

A series of tests of the comparative depth of scour for representative Iowa pier and abutment designs has been completed as a part of the first phase of the project. The most significant aspect of the pier geometry was found to be the alignment relative to the current of all webbed designs. Compared to this effect the shape of the pier shaft itself was of secondary importance. Since abutment shapes differ more than pier shapes do, a somewhat larger effect could be ascribed to their detailed geometry. However, possibly the most important information obtained has been the fact that the scour hole at debris-free abutments is invariably deepest at the upstream abutment corner. This information has an immediate application to design practice, especially in the case of a stub abutment with sheet piling enclosing the earth fill.

Investigation of the first phase - pier geometry - is continuing in the development of shapes which will result in minimum scour. Also in progress is a study of the effect of the velocity and depth of flow on the scour depth - the second phase of the program. Since the rate of sediment transportation is also dependent on the hydraulic characteristics of the stream, a special flume incorporating a sand-feed mechanism and a sand-trap balance has been constructed for this study. The effect of sediment characteristics on the scour process is being studied in a separate investigation sponsored by the Office of Naval Research. Although this companion study cannot be applied directly to the bridge-pier problem because of certain simplifications which it involves, the functional relationships which are being obtained should reduce considerably the experimental program of the third phase. The fourth phase, and the subsequent correlation of field and laboratory measurements, are still too far in the future to warrant detailed comment at this time.

STATEMENT OF PROBLEM

In a sense the prediction of the depth of scour around bridge piers and abutments is only necessary in the justification of the cost of the bridge substructure. It is obvious on the one hand that massive structures carried to bedrock will never be affected by scour, and on the other that the failure of a bridge as a result of undermining represents a large financial loss. Thus, the foundations should be designed with a cost warranted by the consequent reliability and the probable service of the entire structure. An element of risk is still inherently involved, of course, since the scour to be expected is intimately related to the probable maximum flood flow - which is only predictable statistically. However, in order to confine the element of risk to this statistical probability, it is necessary to estimate the scour around the piers and abutments with considerable certitude.

At the present time the judgment of the engineer based uponpast experience is virtually the only criterion for such a prediction. The desirability of comprehensive design criteria is at once apparent - criteria that would embody the stream characteristics of velocity, depth, cross-sectional shape, alignment, and slope; the characteristics of the sediment composing the bed of the stream; and the geometric characteristics of the bridge substructure, the shape of the piers and abutments themselves, and their relation to the stream and each other.

THE PHENOMENON OF SCOUR

The local lowering of a stream-bed elevation which is generally termed scour is caused by a disturbance of the stream's sediment-transport capacity in a limited area such that the capacity to transport is greater than the amount of material supplied. When an obstruction such as pier is placed in a stream, the flow pattern, and therefore the transport capacity, in the area adjacent to the obstruction is radically altered. As the bed material normally at rest is placed in motion by the local increase in capacity, a scour hole develops, which in turn further alters the flow pattern. The inherent time factor involved in the scour process is apparent, since it is a progressive rather than an instantaneous phenomenon. Furthermore, it can easily be seen that the tendency will be for the rate of scour to decrease with time; that is, as the size of the scour hole increases, the velocity and therefore the transport capacity, at the bottom of the scour hole decreases. However, whether an equilibrium condition is attained within finite time, or an asymptotic limit is approached, still is a matter of conjecture.

It would appear, then, that all that is necessary for an analytical solution is a knowledge of (1) the flow pattern around the obstruction, and the change in that pattern as the scour hole develops, and (2) the relationship between the flow pattern along the bed of the stream and the resulting variation in transport capacity. However true this might be, it is equally true that (1) in general no method exists for obtaining the necessary three-dimensional pattern for turbulent, boundary-layer flow around an arbitrarily shaped obstruction, and (2) such empirical sediment-transportation relations as exist are not sufficiently rigorous to be applied to the problem at hand. Fortunately, model studies provide a technique which allows this fundamental gap to be bridged. By varying each basic factor in turn, the effect of each on the scour phenomenon can be assessed. Thus, the model functions as a computer of scour rate or depth as produced by the various boundary, sediment, andflow variables. The limited ability of a model to duplicate exactly the prototype conditions must be recognized, however, and a field as well as a laboratory program is requisite for the development of reliable design relations. Under the sponsorship of the Iowa Highway Commission and the Bureau of Public Roads, the Iowa Institute of Hydraulic Research has undertaken the experimental phase of such an investigation and will cooperate in the later field program.

EXPERIMENTAL PROGRAM AND TECHNIQUES

The laboratory program planned by the Institute has been divided into four nominally independent phases on the basis of the variables to be studied: (1) Geometry of piers and abutments; (2) Hydraulic characteristics of the stream; (3) Sediment characteristics; (4) Geometry of channel cross section and alignment. A portion of the first phase dealing with representative Iowa designs has been completed and reported upon to the Iowa Highway Commission (August 1950), representative results are presented in the next section to indicate efficacy of the laboratory method of attack. Other studies of geometry are continuing, and a study of the effect of velocity and depth of flow on the scour rate and depth is in progress. Different techniques are being used in the studies of the two phases, since the information desired is of a different order of quantification.

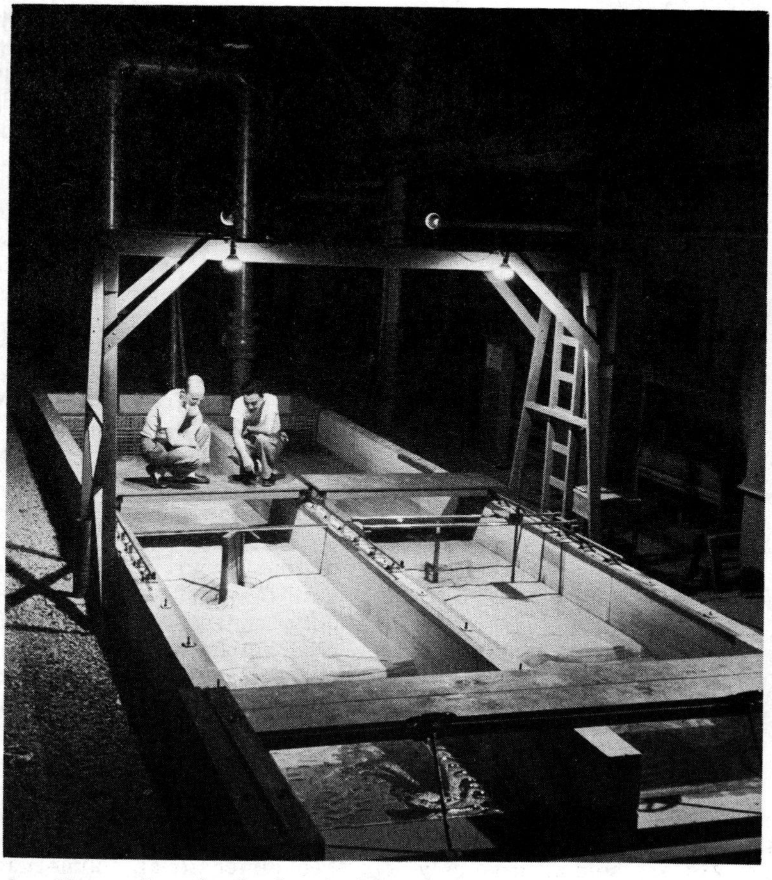

Figure 1. Flumes for the Study of the Effect of Pier and Abutment Geometry

In the investigation of pier and abutment geometry a comparative measure of the scour depth is sufficient. The flumes for the study of this phase are shown in Figure 1. Each flume is 5 ft. wide and 35 ft. long and removal of the center wall converts the two into a single channel slightly over 10 ft. in width. Controls are provided for both the rate and depth of flow, but to date one standard flow condition has been maintained for all experiments. A flow with a velocity of 1.25 ft. per sec. and a depth of 0.3 ft. was chosen on an arbitrary basis of convenience to give a low rate of general movement over the entire sand bed (so that a sand-feed mechanism would be unnecessary), the scour hole then developing at a reasonable rate. A graded sand with a mean size of 0.58 mm. was used in all experiments to obviate sorting. Thus, all factors affecting the scour were kept constant except the geometry of the pier or abutment being studied.

In order to follow the development of the scour hole with time, horizontal layers of red sand 0.01 ft. thick were placed at 0.1 ft. vertical intervals in the vicinity of the pier. This sand was prepared by coloring the natural white

Ottawa sand with an aniline dye (Sudan III in 0.01 percent benezene), which produced no change in the sediment characteristics. As the scour progressed, successive layers were exposed. At the end of the standard three-hour run (which resulted in the establishment of sensibly equilibrium depths) the edges of the red layers appeared as contour lines delineating the scour hole. The scour depth at the end of the run was taken as a representative measure of the effect of the geometry of the various piers and abutments. It cannot be emphasized too strongly, however, that such results are comparative only and should not be interpreted as actual depths of scour to be expected. Even in this limited sense they should be considered tentative until the studies of the second and third phases of the program indicate that they are truly representative over a wide range of flow and sediment conditions.

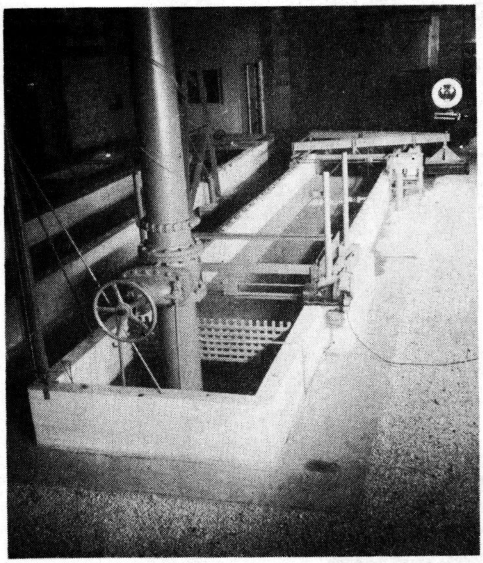

Figure 2. Flume for the Study of the Effect of Stream Characteristics

Since the rate of sediment transportation will vary with the velocity and depth of flow, another flume (Fig. 2) was constructed for the study of the second phase. As well as the usual flow controls, this channel has a sand-feed mechanism and a sand-trap balance. The sand feed is an elevator at the beginning of the test section which can be raised at a known rate to produce a sediment supply equivalent to the rate of transportation. With the sand trap suspended from a balance at the downstream end of the channel, a primary measure of the rate of transportation is obtained. The physical dimensions of the flume are 5 ft. in width, 1.5 ft. in depth, and 30 ft. in length.

For the complete interpretation of the effect of velocity and depth of flow on the scour phenomenon, the rate of scour is required, since it varies with the depth of scour. In order to obtain this detailed information, an electrical scour meter has been developed. The fundamental principle which allows an electrical measure of scour to be made is that the resistance and the capacitance of water and of a water-sand mixture are markedly different. Two vertical electrodes partially imbedded in the sand form one arm of a bridge circuit. The unbalance of the bridge will then depend on the relative elevation of the sand surface.

Investigation of the last two phases of the program is not contemplated until the present studies are considerably more advanced. However, a companion study being conducted for the Office of Naval Research on the effect of sediment size and sorting on the time rate of scour should unquestionably aid in the study of the effect of sediment characteristics in the pier-scour problem. The salient features of the ONR study are a horizontal, two-dimensional, submerged jet flowing along a sand bed initially level with the bottom of the jet. The velocity and thickness of the jet and the characteristics of the sand are varied and the consequent profiles obtained at successive time intervals. Besides the geometric dissimilarity to the pier-scour case, a major difference between the problems is the absence of any transport into the scour hole in the ONR study. At the very least, however, the parameters governing the effect should be transferable. A further consideration in deferring the direct investigation of the third phase is that the flume in Figure 2 can be utilized without modification simply by using other sands.

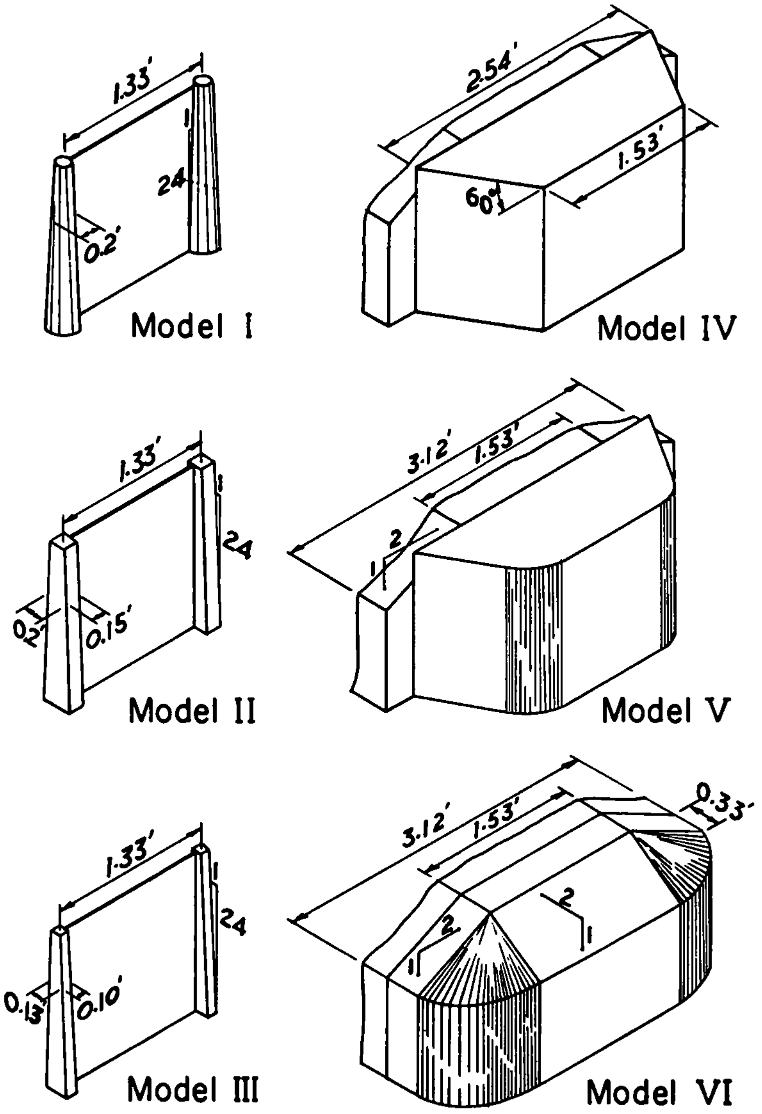

Figure 3. Pier and Abutment Models

Implicit in the last phase is the relation of the bridge (including approaches) to the stream - that is, to flood-plain as well as main-channel flow. The large number of geometric combinations that may obtain precludes the complete investigation of all the possibilities. Moreover, it is reasonable to expect that the results of the preceding phases will allow recognition of the more important factors and, therefore, simplification of the experimental program.

Not until the completion of the first three phases will it be possible to analyze field data. Even then it will probably be necessary to restrict the field measurements to selected sites approximating the ideal or simplified laboratory conditions. Model studies of specific installations as a part of the last phase, however, might allow the field program to expand rapidly. Necessary for the proper interpretation of the scour data from the field is a continuous record correlated with the stream-flow record. Modification of the electrical scour meter used in the laboratory may provide the means of obtaining such a record.

TESTS ON REPRESENTATIVE IOWA PIER AND ABUTMENT DESIGNS

The term "representative designs" has been used advisedly in this phase of the study, since the many possible examples were reduced arbitrarily to the forms shown in Figure 3. A simplified, but still typical, geometry of the piers used with most truss bridges is the circular, battered form of Model I. The two square forms are typical of the piers used with rigid-frame reinforced-concrete bridges; two models were tested, since the pier shafts for this type of bridge are generally smaller than the circular, as in Model III, and tests were hence also desired with shaft of equal size, as in Model II. All three models were tested with and without a web, and at various angles to the stream current.

In a similar manner the abutment models represent generalized designs: the sloping form, Model VI, typifies the stub abutment with the earth embankment enclosed by sheet piling and protected by concrete pavement; the vertical form, Model IV, corresponds to a gravity retaining wall at the end of the approach fill. Since high velocities might be expected at the sharp corners of Model IV, a form with rounded corners, Model V, was also tested. A variable length of approach fill was also included as a pertinent factor in the abutment tests.

Many features of the scour phenomenon can be more clearly understood by analyzing the progress of the scouring action around a typical pier. At the outset, with the bed level, the flow around the pier is essentially two-dimensional - i. e., in horizontal planes. Although sediment transportation is then general, the capacity is obviously higher at points of high velocity such as at the corners of the rectangular shaft (Fig. 4). Local scouring therefore begins immediately, forming two depressions centered on the corners. These depressions are conical, since the material will not stand at a slope (Fig. 4a) greater than the angle of repose. As the scour progresses, the separation vortex, or roller, occurring across the upstream face (Fig. 4f) is intensified to the point of becoming the active scouring mechanism. Material is carried out of the hole by the spiral continuation of the vortex along the sides of the pier (Fig. 4e). As the depth increases, the sides of the hole slough, and this material must be removed for the hole to continue growing. The same consideration is true for material reaching the hole by general transport from upstream. Since the velocity of the roller is dependent on the size of the scour hole, the rate of removal will progressively decrease with increasing depth of scour. Although the exact pattern of movement varies with the geometry of the pier or abutment, the same action has been noted in all of the tests.

The typical detailed scour patterns shown in Figure 5 illustrate the several general characteristics common to all the piers. The upstream portion of the hole has the approximate form of an inverted cone, sometimes distorted from the circular, with side slopes equal to the angle of repose of the sand. The greatest depth is displaced slightly upstream from the face of the pier. Deposition which occurs in the low-velocity area behind the pier divides the downstream portion of the scour hole into two separate tails.

In the absence of a web, a separate scour hole is formed at each shaft of the pier. At small angles of approach the downstream shaft is shielded, with an accordingly shallower scour hole. As the angle increases, however, the

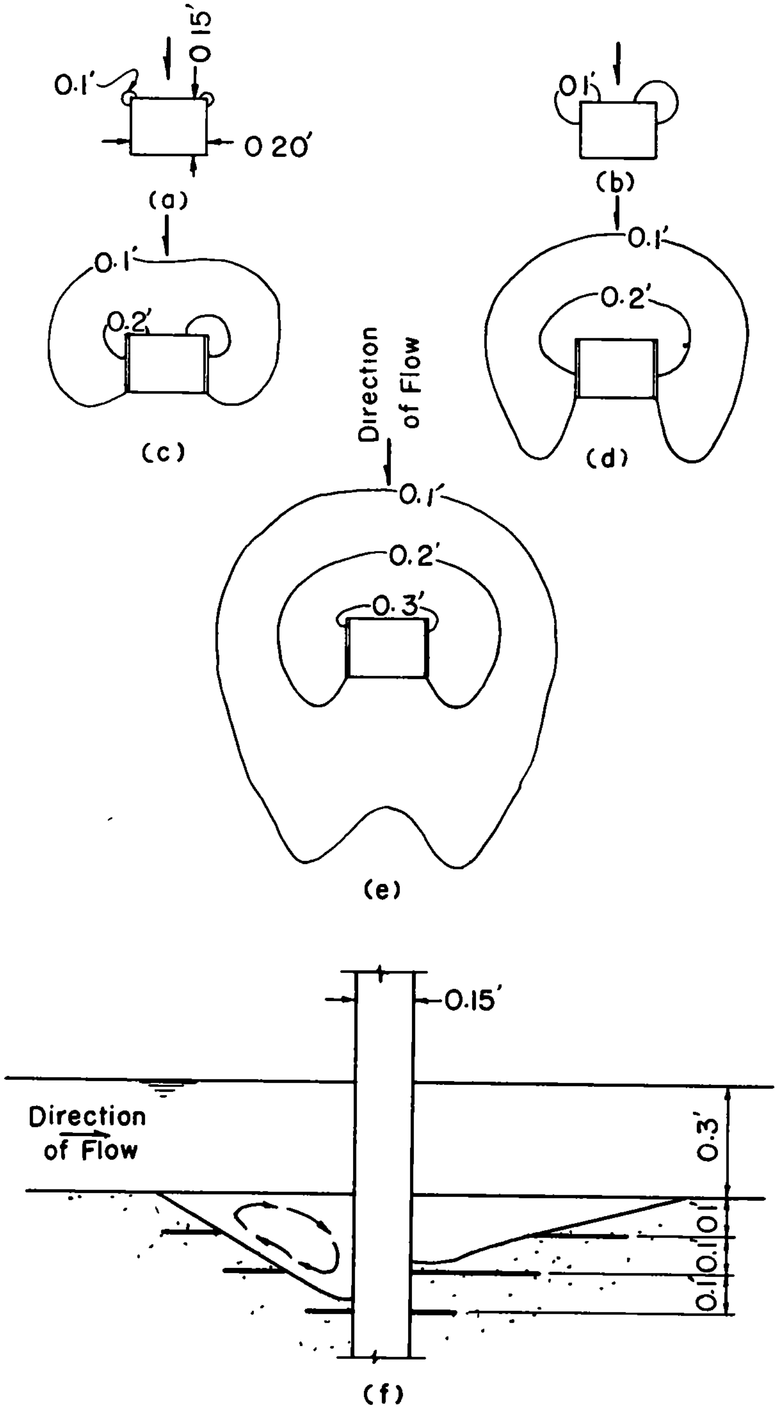

Figure 4. Development of a Scour Hole

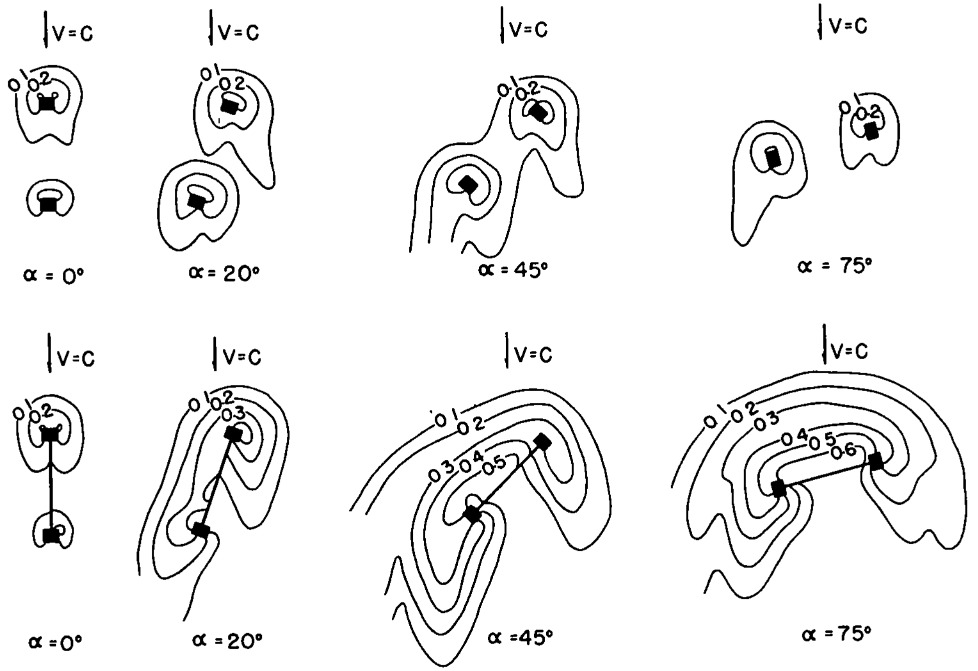

Figure 5. Scour Patterns Around Model II

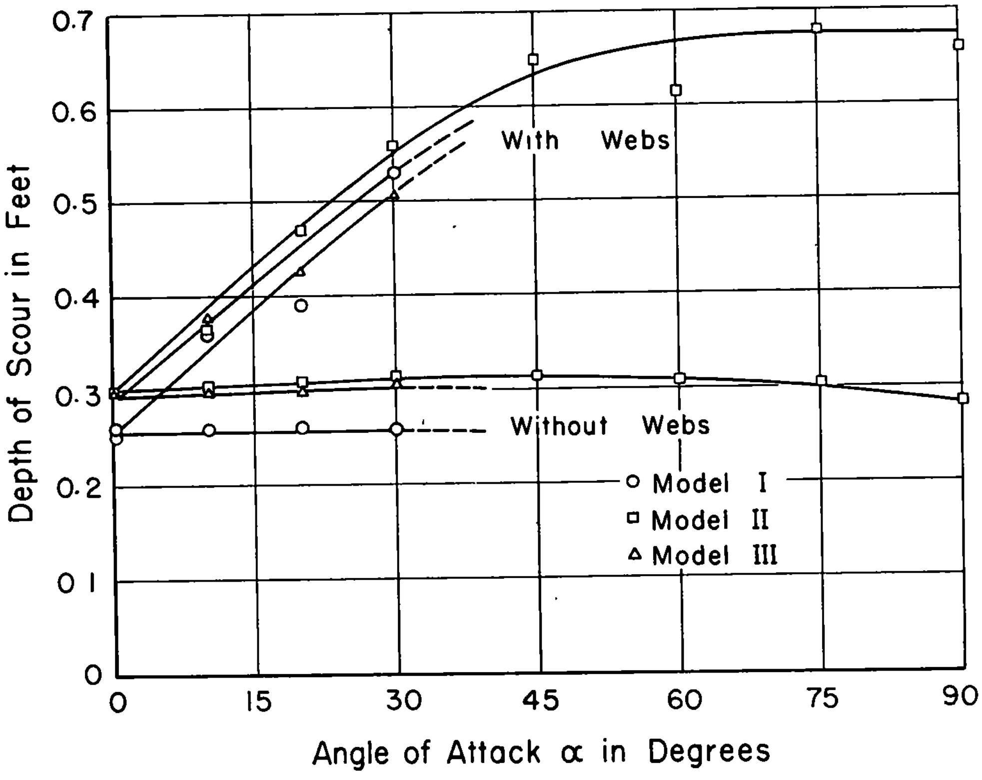

Figure 6. Maximum Depth of Scour Around Model Piers

downstream shaft becomes subject to currents of higher velocity deflected from the upstream shaft so that the deepest scour occurs in the downstream hole. At large enough angles, of course, the two shafts are virtually independent.

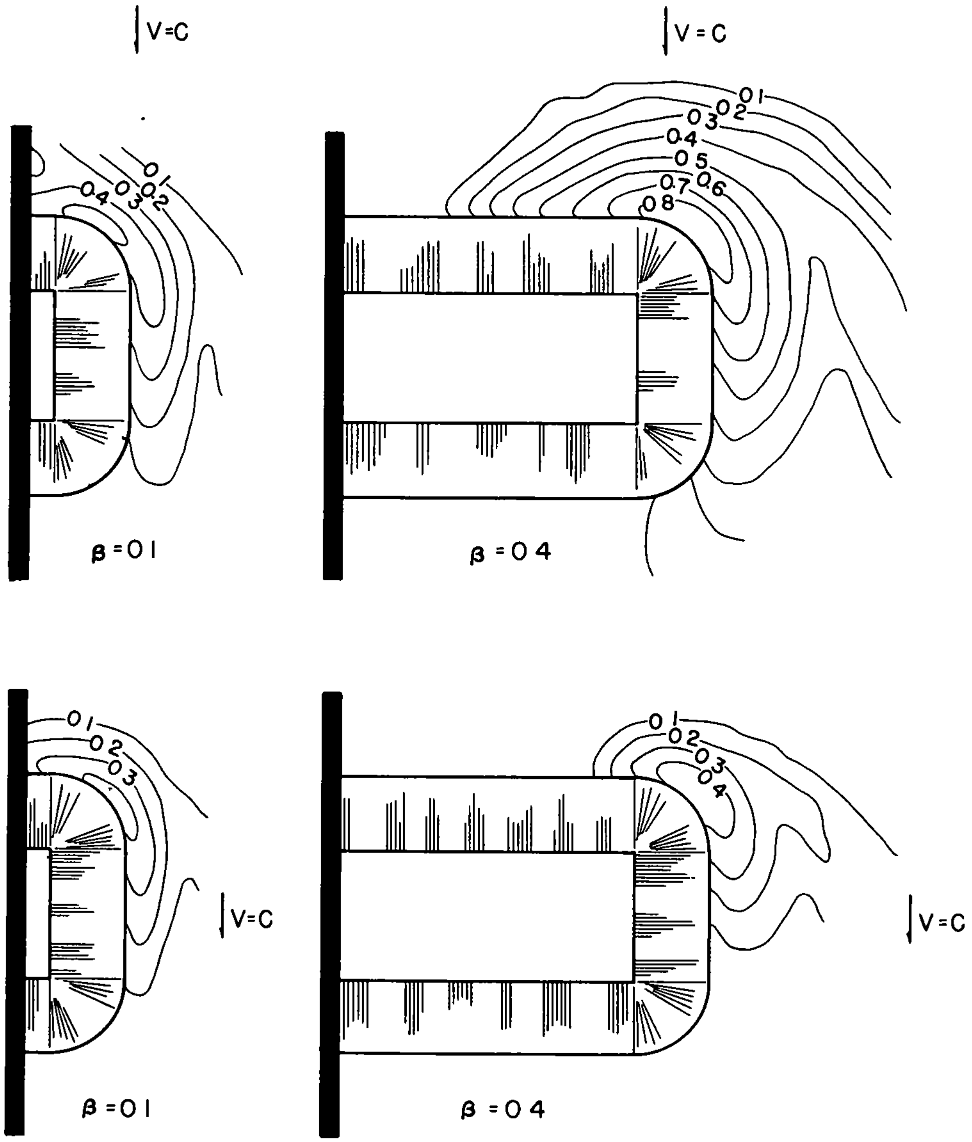

Figure 7. Scour Patterns Around Model VI

When the pier is parallel to the flow, the presence or absence of a web is immaterial. At increasing angles, however, basically different patterns obtain. The web then has a pronounced effect - a scour depth twice as great being attained at an angle of 30 degrees and two and one-half times as great at 45 degrees.

The relative influence of shape and skew angle is clearly evident in Figure 6, in which depth of scour is plotted against angle of attack for each model.

Although shape has a minor effect, it is definitely shown that the higher local velocities resulting from the sharp corners of the rectangular shaft increase the scour depth some 15 percent beyond that for a cylinder of the same breadth. A similar comparison of the structurally equivalent round and rectangular piers (i. e., the round and the small rectangular) must be qualified due to a scale effect. It is believed, however, that the equivalent rectangular pier will produce a slightly greater scour depth.

For the abutment forms, the history of the scour-hole formation is essentially the same as that for the piers even though the flow passes - and hence the scour occurs - on one side only. The shape of the scour hole was strikingly similar for all the models tested. Some of the typical patterns are shown in Figure 7, from which it can also be seen that the length of approach affects the depth more than it does the shape of the hole. Although the velocity of approach was held constant in one series of runs with variable length of fill, the contraction effect on the mean velocity was never sufficient to cause a general lowering of the bed. In the other series with the mean velocity in the contracted section held constant (Fig. 8), approximately the same depth of scour was obtained for all lengths of abutment. Although this is a strong indication that the mean velocity in the contracted section has a primary significance, the proof is not altogether conclusive. It is the local velocity

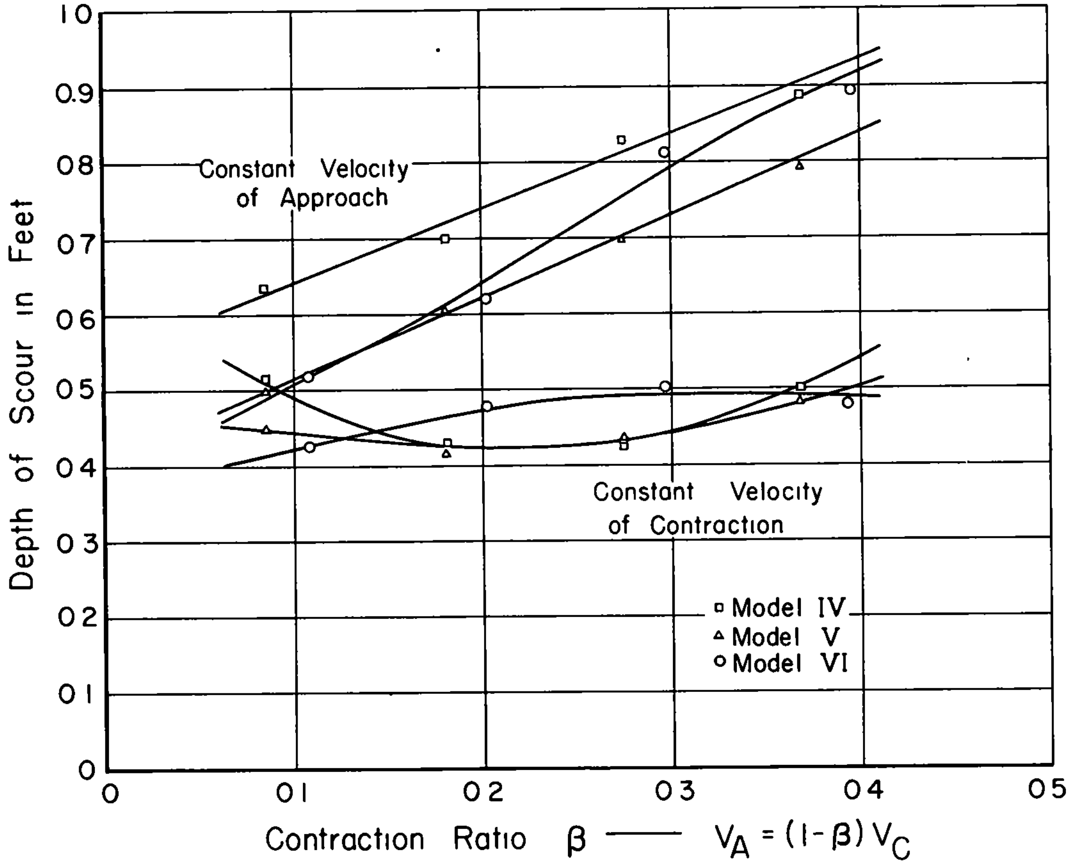

Figure 8. Maximum Depth of Scour Around Abutment Models

variation, rather, that results in the scour - and the existence of a single criterion would be surprisingly fortunate.

A multitude of geometrical combinations are possible in studying the interrelation of piers and abutments. For exploratory purposes, tests were made on a combination of the stub abutment and a full-webbed pier. Very little change could be noted in the scour adjacent to the abutment, but the scour pattern around the pier was similar to that which would occur if the pier were placed at an angle of 45 degrees to the current. It would seem then that the pier exerts little influence on the flow around the abutment, but that the abutment, in effect, swings the current against the pier. While the importance of investigating situations such as this is obvious, the plethora of possible combinations also makes it evident that the work should be postponed until more is known of the scour process.

Although these experiments on typical Iowa designs necessarily indicate relative rather than actual depths of scour, several conclusions of immediate practical significance can already be drawn. In the first place, the danger of placing webbed piers at an angle to the current is clearly illustrated, even small angles having an appreciable effect upon the scour. Predicting the direction of flow in a constantly changing river is assuredly not an easy matter. However, since the greatest danger occurs during flood flows, the valley line appears to be the primary factor to consider in determining pier alignment. In the second place, the basic scour pattern of the abutments clearly indicates those portions of the structure requiring the greatest stability or protection. For the gravity-type abutment, it would probably be impractical to construct a concrete wall to a variable depth for equivalent foundation safety. However, supplementary protection such as sheet-piling or sunken revetment could be applied economically. For the stub type, on the other hand, the sheet-piling enclosing the embankment could easily be driven to a variable depth, providing maximum safety without undue expense. The paving or riprapping of the slopes should be planned in the same manner, the upstream corner and neighboring slopes receiving the greatest protection.

CONCLUSIONS

Although the results of the comparative study on the effect of the geometry of representative Iowa pier and abutment designs have been presented herein as a self-contained unit, all conclusions are subject to re-evaluation and qualification on the basis of further studies. For example, the relative magnitude of the scour depth for the various geometric forms could differ if the flow conditions or bed material were changed, but it is unlikely that the relative rank would differ. Likewise, a combination with stream channel geometry may reduce, but would not invalidate, the significance of some of the conclusions.

In line with the opening argument relating the scour problem to construction costs, two approaches to the ultimate solution are evident - the prediction of scour depth around the commonly employed pier and abutment forms, and the development of forms or methods of protection resulting in lessened scour. To date the program of this investigation has been largely confined to the first approach, not only in its own right but also as necessary to the proper evaluation of any developments resulting from the second type of study. As an example, the continuing study of pier forms for hydraulic effectiveness must finally be interpreted from the viewpoint of structural requirements and construction practice. Similarly, the practicability of such protection devices as riprap, usually employed as a maintenance measure, can only be properly assayed after the completion of the third phase of the investigation.