HIGHWAY RESEARCH BOARD

Research Report No. 13-B

SCOUR AROUND BRIDGES

1951

HIGHWAY RESEARCH BOARD

1951

OFFICERS

Chairman .... R. A. MOYER
Vice-Chairman .... R. H. BALDOCK
Director .... ROY W. CRUM
Associate Director .... FRED BURGGRAF

EXECUTIVE COMMITTEE

THOMAS H. MacDONALD Commissioner, Bureau of Public Roads

HAL H. HALE Executive Secretary, American Association of State Highway

retary, Division of
and Industrial
National Research

eer, Oregon
nmission

ive Safety

affic Engi-
American
on

stitute of
nd Traffic
rsity of

Missouri
rtment

eer, Iowa
nission

N. Carey, Jr.

ne statements

ton 25, D. C.

HIGHWAY RESEARCH BOARD

Research Report No. 13-B

SCOUR AROUND BRIDGES

PRESENTED AT THE THIRTIETH ANNUAL MEETING
1951

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL RESEARCH COUNCIL

Washington 25, D. C. April 1951

DEPARTMENT OF HIGHWAY DESIGN

C. N. Conner, *Chairman*
Principal Highway Engineer, Bureau of Public Roads

COMMITTEE ON SURFACE DRAINAGE OF HIGHWAYS

Carl F. Izzard, *Chairman*
Chief, Hydraulics Research Branch
Bureau of Public Roads

Richard Ackroyd, Drainage Engineer, Bureau of Public Roads
C. A. Betts, 16 Winston Drive, Bethesda, Maryland
Tate Dalrymple, US Geological Survey
Neil J. McMillen, Drainage Engineer, Ohio Department of Highways
Howard F. Peckworth, Managing Director, American Concrete Pipe Association
R. Robinson Rowe, Supervising Bridge Engineer, California Division of Highways
R. M. Schwegler, Senior Highway Engineer, Bureau of Public Roads, Portland, Oregon
George E. Shafer, Chief Engineer, Armco Drainage and Metal Products, Inc.
G. S. Tapley, Bureau of Engineering, City of Los Angeles
Homer R. Turner, Engineer of Highway Drainage, Connecticut State Highway Department
Gordon R. Williams, Associate, Knappen, Tippetts, Abbett Engineering Company
W. S. Winslow, Hydrographic Engineer, North Carolina State Highway and Public Works Commission

CONTENTS

FOREWORD

The Committee on Surface Drainage of Highways presents herewith two papers dealing with the problem of scour around bridges. The first paper "Model Studies of Scour Around Bridge Piers and Abutments" is a progress report on a cooperative investigation financed by the Iowa State Highway Commission and the United States Department of Commerce, Bureau of Public Roads. Work on this project, begun in 1948, is still continuing at the Iowa Institute of Hydraulic Research, Iowa City, Iowa.

The second paper "Investigation of Flexible Mats to Reduce Scour Around Bridge Piers" is a report on a project conducted by the Rocky Mountain Hydraulic Laboratory in cooperation with the United States Department of Commerce, Bureau of Public Roads. The work was done during the summer of 1950 at Allenspark, Colorado.

Both papers clearly indicate that much additional investigation is needed, not only in the laboratory but also in the field. The Committee will appreciate suggestions regarding practical methods of observing scour around bridges during flood stages, particularly regarding tested methods. It will also welcome detailed information on scour problems at specific bridge sites which might be studied in the field either for the purpose of correlation with laboratory results on the fundamental principles of scour or for the purpose of evaluating flexible mats placed, or to be placed, to reduce scour.

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

Emmett M. Laursen
Iowa Institute of Hydraulic Research
State University of Iowa

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.

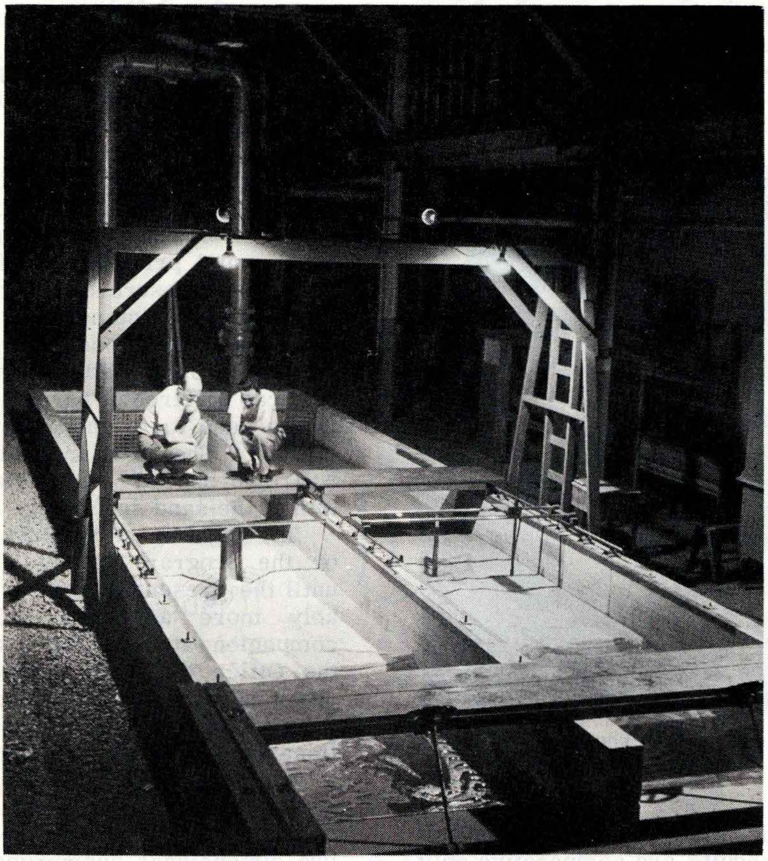


Figure 1. Flumes for the Study of the Effect of Pier and Abutment Geometry

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.

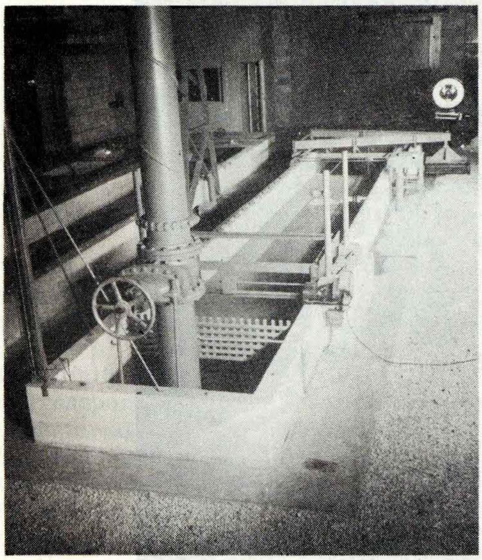


Figure 2. Flume for the Study of the Effect of Stream Characteristics

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.

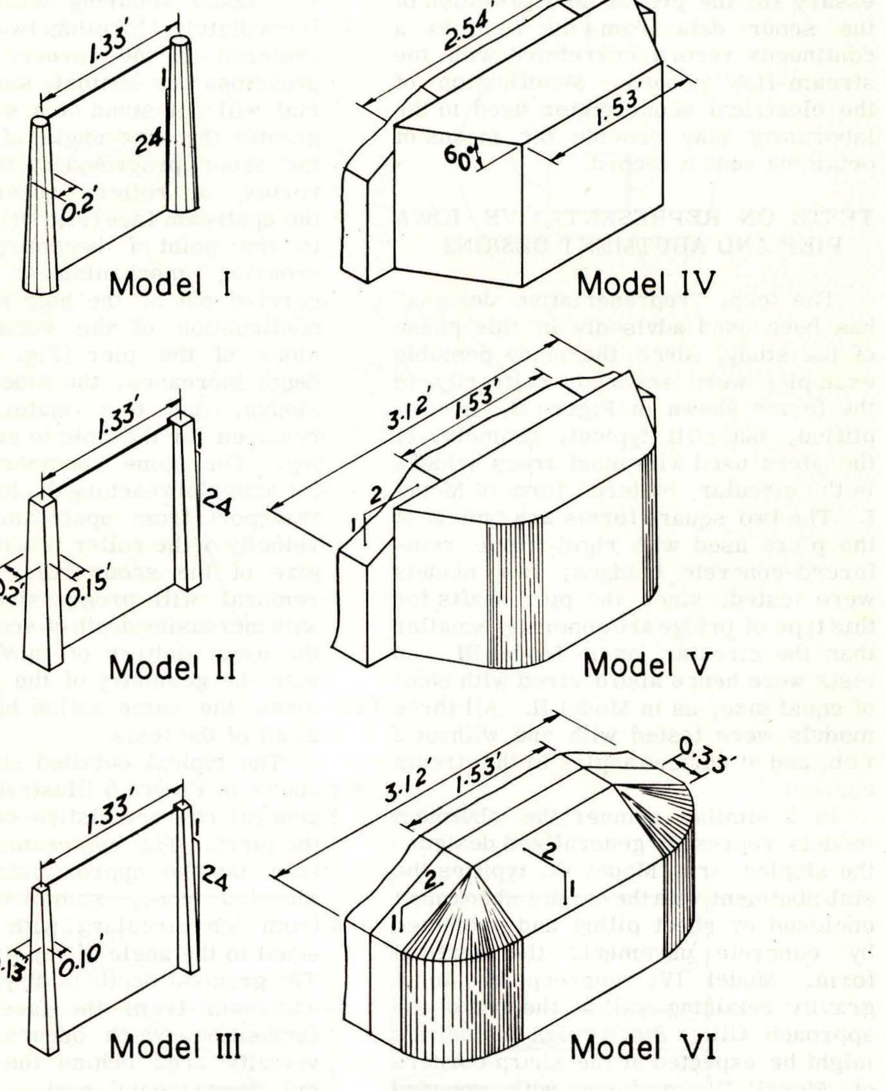


Figure 3. Pier and Abutment Models

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

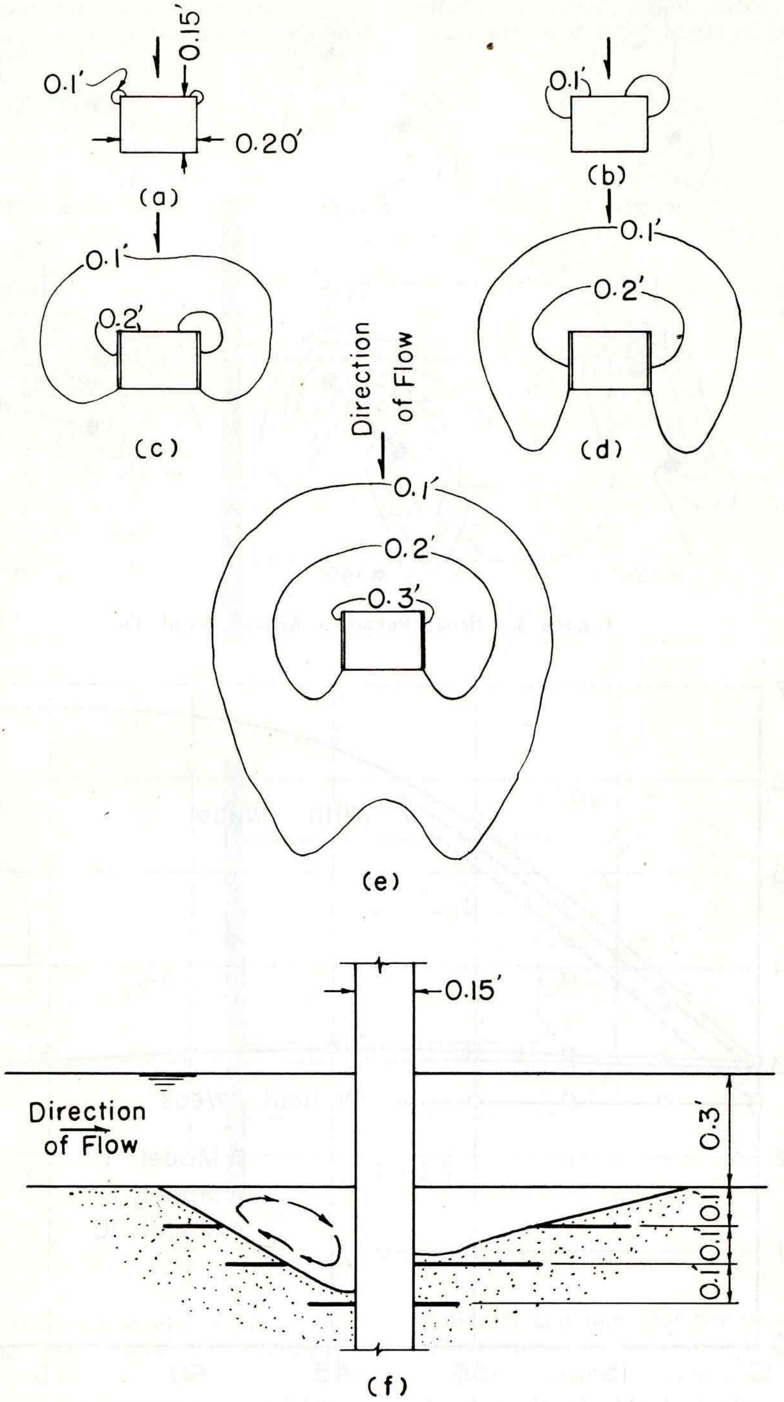


Figure 4. Development of a Scour Hole

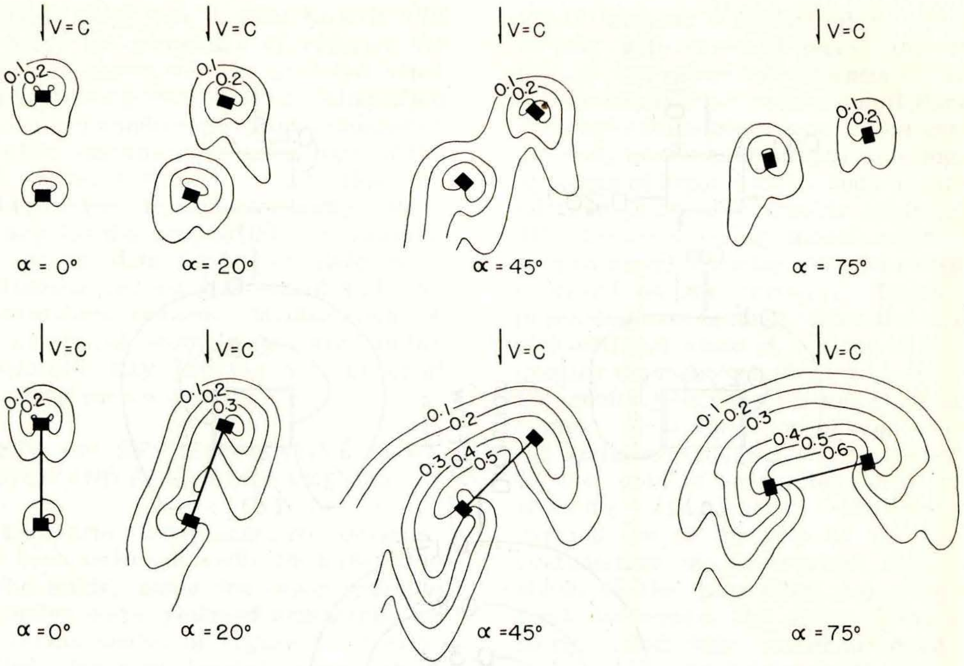


Figure 5. Scour Patterns Around Model II

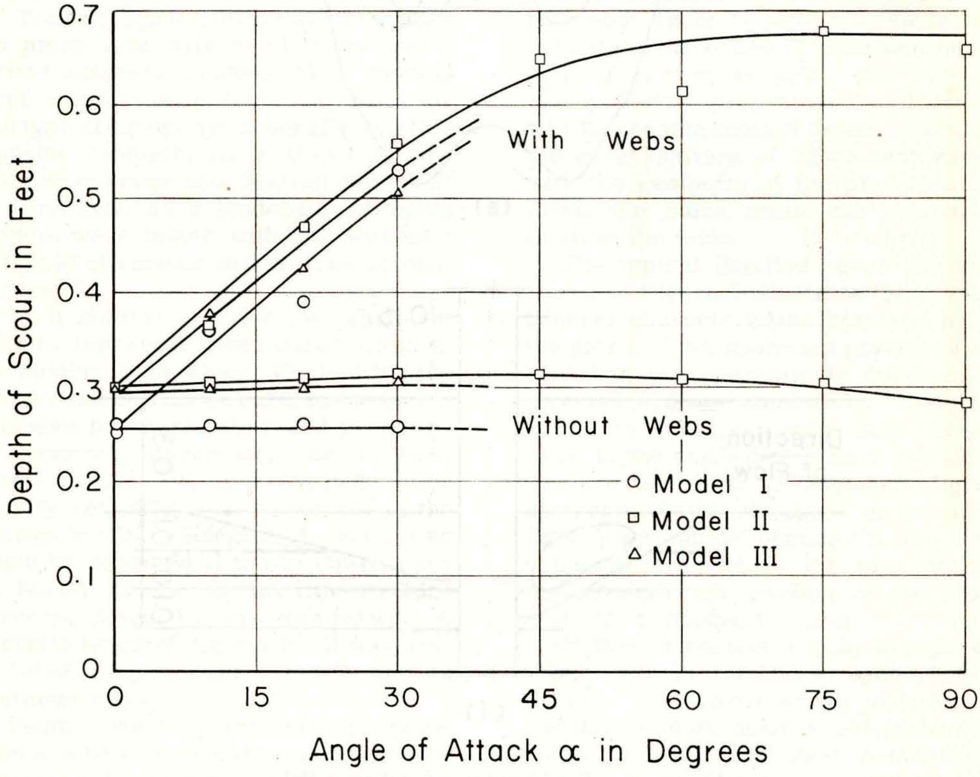


Figure 6. Maximum Depth of Scour Around Model Piers

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.

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.

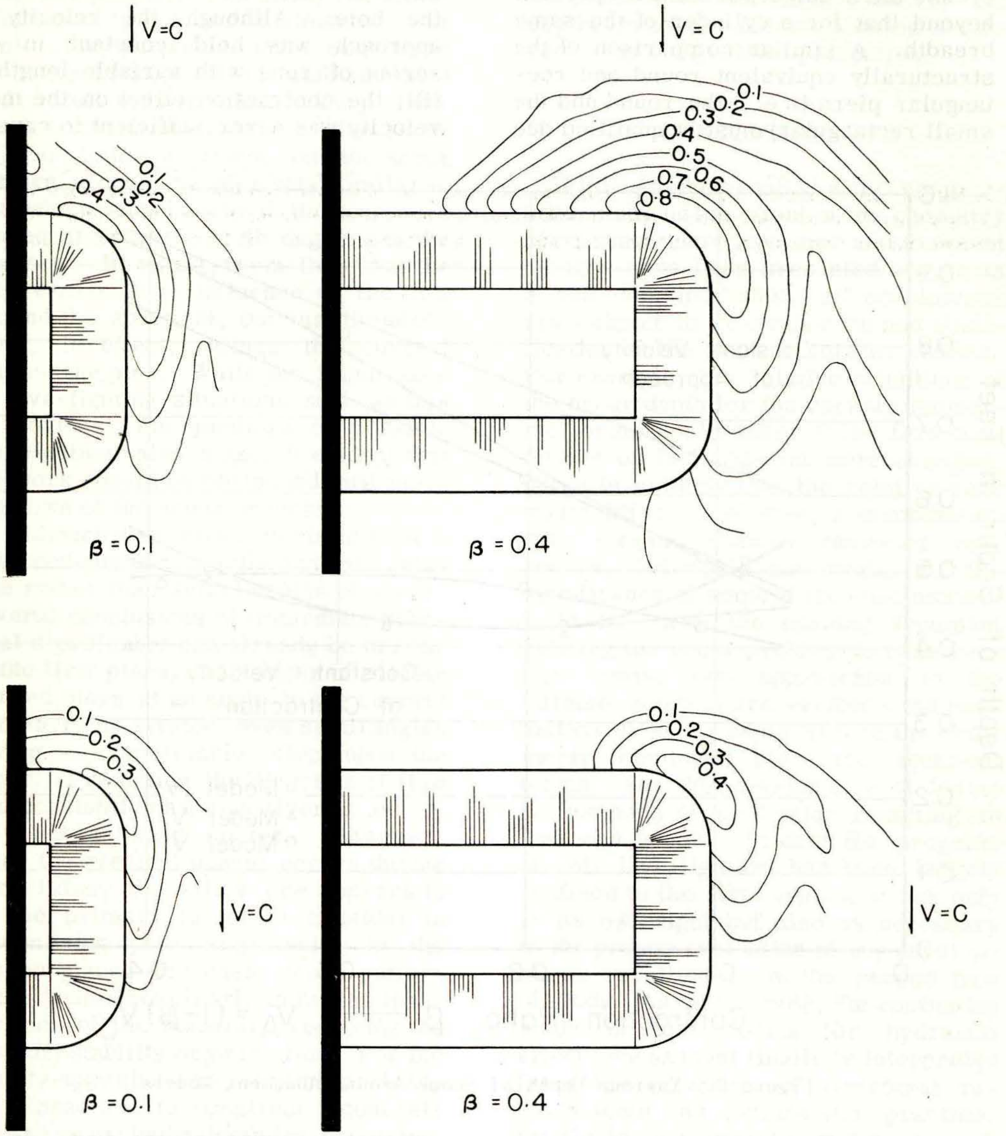


Figure 7. Scour Patterns Around Model VI

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

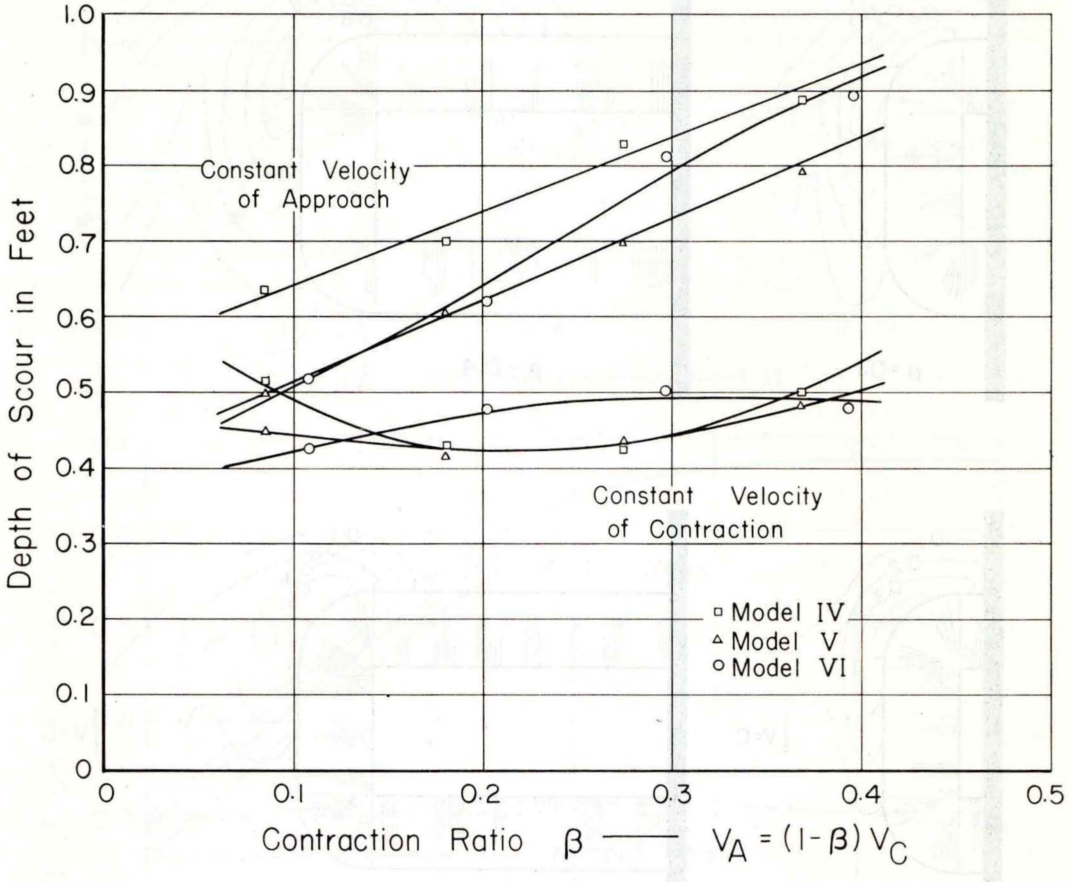


Figure 8. Maximum Depth of Scour Around Abutment Models

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.

INVESTIGATION OF FLEXIBLE MATS TO REDUCE SCOUR AROUND BRIDGE PIERS

C. J. Posey and D. W. Appel, State University of Iowa, Iowa City,
and E. Chamness, Jr., Colorado A and M College, Fort Collins

SYNOPSIS

Experiments to investigate the possibility of protecting bridge piers in erodible material by means of flexible mats placed around the piers were made by the Rocky Mountain Hydraulic Laboratory in cooperation with the United States Bureau of Public Roads. Observations of the performance of a number of types of mats were made with the aid of a 6-in. diameter transparent pier in a flume 80-in. wide, with depths of flow ranging up to 18 in. The bed was of non-cohesive material and observations were made under both equilibrium and degrading conditions.

It was found that the two greatest hazards to the effective functioning of such mats were (1) the tendency of upward currents to move material up through the mat, and (2) the tendency of the mat to bridge or buckle due to bottom irregularities, thus opening up underchannels through which bed material is easily transported away. The upward currents result from underflow driven by the pressure differential existing between the stagnation zone and nearby zones where the pressure may even be less than hydrostatic. At the point where this underflow rises the bed may become "quick". It is impractical to seal off the underflow with an impervious mat because the greatest pressure occurs next to the pier where water-tightness would be difficult to attain, and because the mat would have to be extremely thick to seal off possible upward flow by sheer weight.

The necessity for the mat to conform to bottom irregularities may arise at the time of installation, if that be attempted during flood, or even after installation under ideal conditions, during the subsequent passage of fortuitous bed irregularities such as sand waves.

The best protection was afforded by a heavy completely flexible mat with comparatively small openings. Prototype construction of such a mat could be from worn chains, which with hot-dip galvanizing should have long life. Placing gravel under the mat at the time of installation greatly improved its effectiveness. The size of the gravel was such that it would be unable to pass through the mat. The combination, which apparently functioned as an inverted filter in preventing bed material from being carried up through the mat, provided complete protection against local scour around the pier until the bed of the entire stream had degraded to such a low elevation that the chain mat was no longer able to follow the bed down around its periphery.

A full-scale test is recommended, with later systematic investigation of the proper net diameter if prototype results show possibilities of economical and effective functioning.

THE SCOUR PROBLEM

In designing bridges to be built on erodible foundation material, the engineer must consider not only the possible general lowering or degrading of the stream bed in the vicinity of the bridge, but also the additional localized lowering caused by increased velocity and turbulence due to bridge piers and abutments. Practically the only solution to this problem that has had widespread use is to construct the piers and abutments to an elevation low enough that their stability will never be endangered.

Unfortunately the prediction of the maximum depth of scour has had to be based upon rules-of-thumb or local records, often untrustworthy. It seems that considerable research remains to be done before any rational method of estimating either component of the total depth of scour can be developed. Apparently India is the only country in which scour records have been the subject of much study (1)[1]. Empirical relationships which have been obtained there are summarized in the appendix to this paper.

Alternatives to carrying the piers down below the maximum possible depth of scour are finding a shape of pier

---

[1] Figures in parentheses refer to references listed at the end of this paper.

that will minimize scour, or protecting the bed around the pier so that it will not scour deeply. It is the latter method which offers possibilities of economically increasing the safety of existing structures, that forms the subject of the present investigation.

GENERAL STREAM-BED LOWERING AT BRIDGE SITES

Bridges are usually located at sections where the stream is naturally narrow and its banks steep. The amount of waterway area added by a rise in stage, at such locations, is less than at wider sections, so that during flood times the velocity is increased, relatively, at the narrow sections[2]. This means that during floods the bed material will be scoured out from the narrow sections and deposited in the wider sections. The bridge foundations and approach fills still further constrict the stream, frequently causing the bed to scour out to extreme depths during high water, only to fill up again when lowered velocities permit the deposition of sand washed down from the deposits left in the wider sections of the river. Local observations of this general lowering of the stream bed at constricted sections give rise to such rules-of-thumb as "for every foot rise of the water surface, the bottom drops two feet." Of course, the amount the bottom drops per foot of water-surface rise depends upon whether the particular local percentage of constriction is low or high. It may be as much as four feet, or even more. Although the exact amount of bed degradation cannot be predicted, the phenomenon must be taken into account in evaluating possible methods of protecting bridge piers from scour.

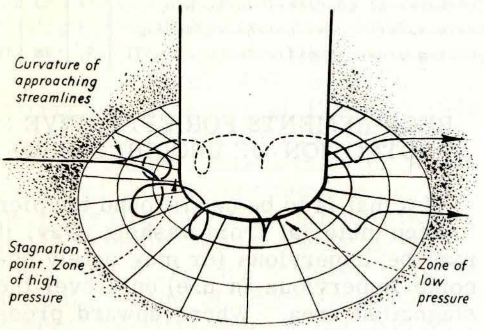


Figure 1. The Scour Spiral at the Base of a Pier Protected by a Mat

SCOUR EFFECT OF FLOW PATTERN AROUND PIERS

As the stream lines approach the pier, they are deflected to the right and to the left. Separation occurs at about the widest section of the pier, and a turbulent wake forms downstream. This is the two-dimensional pattern of flow, as seen from above, and it is a familiar one since many types of cross-sections have been studied as airfoils. The three-dimensional aspects of the flow are more important in our problem, however. As the main current is deflected, a spiral flow is formed, according to the principles first described by James Thomson. The spirals which tend to form on each side agree in direction, and indeed they join to form one continuous eddy across the nose of the pier. Its direction is downward next to the pier. Its size and strength depend upon the main-current velocity distribution in the vertical and upon the geometry of the space available. If the main-current vertical velocity curve has a "turn-back" near the surface (velocity at water-surface less than that below) a smaller spiral, in the opposite direction, will form near the water surface. Evidence of this upper spiral can frequently be observed from above. It is the bottom spiral, however, that tends to excavate a scour hole around the pier.

This typical mechanism of local scour was observed around a circular transparent pier at the Laboratory in the summer of 1948 (2). It was also observed at the laboratory at Poona, India, for flow around piers modeled to

---

[2] The exceptional case of torrents flowing at velocities great enough to permit a standing hydraulic jump to form is not considered here.

scale after those of the Hardinge bridge (1).

During the present tests, it was noticed that the size and intensity of the spiral was influenced by the geometry of the bed. In particular, the scour eddy was intensified at certain stages of the passage of a sand wave, and was of maximum destructiveness when the sand wave crest happened to be oblique to the current. It is known that in such a case the sand wave itself can shed an eddy or kolk of considerable intensity.

Consideration of the mechanism of scour around a pier gives a clue to one method of protection. If the radius of curvature of the main stream lines diverging so as to miss the pier can be increased, the strength of the spiral will be decreased. This method has been tried in Belgium, where it was found that piles driven upstream from the pier in appropriate patterns protected the pier from scour (3). While this method seems well adapted for use in tide-water regions, its use over most of the United States would seem to be prohibitively expensive. The principle is important, however, for it explains the mechanism by which the upstream pier of a pair "protects" the pier downstream from it.

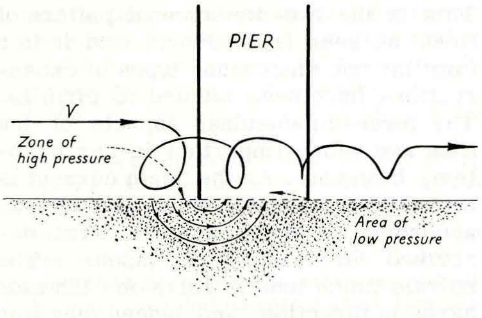


Figure 2. Underflow at Base of Pier

UNDERFLOW PATTERN AND ITS EFFECT

At the bottom of the stream, next to the upstream edge of the pier, is a "stagnation" point, where the water momentarily comes to rest before flowing to one side or other of the pier. The pressure at the stagnation point is greater than the static pressure by a full velocity head. Nearby, a short distance around the pier, the water pressure is no more than static, and very likely less, because of the three-dimensional curvilinear flow. If the bed is porous, underflow will occur between these nearby regions of high and low pressure. Where the flow rises, the bed may become "quick". A simple computation suffices to show the futility of attempting to protect the bed by means of an impervious mat heavy enough to stop this upward flow (see Table 1).

TABLE 1

Maximum velocity in ft. per sec.	2	6	12	20
Thickness of concrete, in inches, heavy enough to withstand corresponding pressure difference	1	9	38	108

REQUIREMENTS FOR EFFECTIVE PROTECTION OF ERODIBLE BED

If a mat is to be used around the pier to keep material from washing away, it may be impervious (or may safely become impervious in use) only over the stagnation area. Where upward pressures may occur, the mat must have a high enough ratio of porosity to weight to permit the water to flow upward without exerting sufficient force on the mat to raise it. At the same time, the interstices in the mat must be small enough or so shaped that the bed material does not tend to pass upward through it. Theoretically, this calls for the use of an inverted filter under any thin-type mat since one with fine enough mesh to hold sand would be likely to clog, or would be too fragile for prototype use.

The existence of upward flow, with a tendency for the bed to become "quick", makes it theoretically necessary to underlay heavy stone riprap, if this is used for protection from scour, with an inverted filter. However, imperfect inverted filters, built with only one layer of finer stone, have given good results.

An additional requirement for any

protective covering put on the bed around a pier to prevent scour is that it should be flexible and extensible and contractible in such a way that it can lay on a non-planar bed of complicated shape, maintaining close contact at every point. If the mat cannot do this, its curving downward to meet the degrading bed at one point on its periphery may cause it to buckle upwards at some other point, presenting an obstacle which may deflect the current enough to cause significant pressure differences, and providing an underchannel through which the bed material is easily swept away.

SCOPE OF PRESENT TESTS

The foregoing analysis is based largely on the findings of a series of model tests made at the Rocky Mountain Hydraulic Laboratory at Allenspark, Colorado. Preliminary tests were made in a flume 6 ft. wide by 22 ft. long during the summers of 1948 and 1949 (2, 4). A cooperative agreement with the United States Bureau of Public Roads in effect during the summer of 1950 permitted the building of a larger flume, approximately 80 in. wide by 30 ft. long, and especially designed to facilitate the testing of scour around bridge piers. The objective of the 1950 tests was the investigation of flexible mats for scour prevention. The only shape of pier tested was the round circular pier, it being reasoned that if the requirements for a mat that would provide satisfactory protection for that type of pier could be determined, it would then not be too difficult to find the requirements for pier of more complicated shape. For similar reasons, the investigation was restricted to the case of cohesionless bed material. While it was realized that the requirements for cohesive bed materials might be significantly different, it is known that non-cohesive bed materials are by far the most common at the sites of permanent-type bridges. Except for one test, the diameter of the pier was approximately 6 in. The depth of flow ranged from about 1 to 1-1/2 ft., and average velocities from 0. 8 to 1. 4 ft. per sec. The bed material was a fine bank sand.

Every practicable type of mat suggested was tested. Tests were also made of the scour when no protection was provided, and when gravel riprap protection only was provided. Time did not permit the systematic investigation of the effects of certain variables which were found to be important. Improvements in the apparatus and the technique of testing were made whenever the possibility of doing so became apparent, even though making changes invalidated, to some extent, the accuracy of quantitative comparisons. The aim was to find out, as completely as possible, the design requirements for protective mats.

METHOD OF CONDUCTING THE EXPERIMENTS

The experiments were made in a specially-constructed concrete flume built along the north bank of the North St. Vrain Creek on the Laboratory's property near Allenspark, Colorado. By means of needle dams and a conduit from above the head baffles to the weir box, the water of the creek could be shut out from the flume, introduced onto the model from both upstream and downstream, or passed through the flume for hours with a constant discharge.

With the by-pass gate immediately upstream from the flume closed, needle boards stopping flow through the upper baffles were removed as required to obtain the desired discharge with a fairly uniform velocity distribution. A baffle rack with enough constriction to cause a water-surface drop of one or two tenths of a foot for the desired discharge was in place across the upper end of the flume. The resultant velocity distribution in the flume upstream from the model pier, which was 11 ft. 8 in. downstream from the baffles, was fairly uniform, although a slight lack of uniformity, with the velocity high near the edges and low in the middle was occasionally observed.

In preparation for a test, sand that had washed downstream from previous tests was shoveled toward the head of the flume and then struck off to a constant depth (4 in. in most cases) above the flume bed. The mat was in some instances placed at this time, in others it was placed after flow was established. The bed was next carefully inundated from both upstream and downstream to avoid washing gullies in the sand. After the bed was covered to a depth of a little over a half a foot, water started flowing over the measuring weir, and the discharge was rapidly increased until the desired reading on the weir gage was obtained. At the same time, the sand feed was started. Fine sifted pit sand was fed by hand at a rate of 2. 6 lb. per min. , care being taken to see that the sand bed developed as uniformly as possible. This rate of sand feed closely approximated that required for equilibrium conditions with the discharge depth, and slope. These equilibrium conditions were established by preliminary tests in which the elevation of the weir crest was varied, not the rate of sand feed, which had to be a convenient rate. The bed formed a rippled surface with ripples averaging 0. 2-0. 3 ft. apart and not over 0. 05 ft. high. The pit sand contained a high percentage of fines that tended to wash out. Sieve analyses of samples of the sands made by the Bureau of Public Roads Division Office in Denver gave the results shown in Table 2.

The bed was prepared from sand that was more and more thoroughly washed, as the experiments progressed, while the sand feed was always fresh pit sand. For this reason differences in protective characteristics of the various mats cannot be taken as significant unless they are large. The comparison of the four runs with no protection, Figure 3, gives an idea of the range of non-uniformity since these runs were made at times ranging from near the beginning until near the end of the summer's tests.

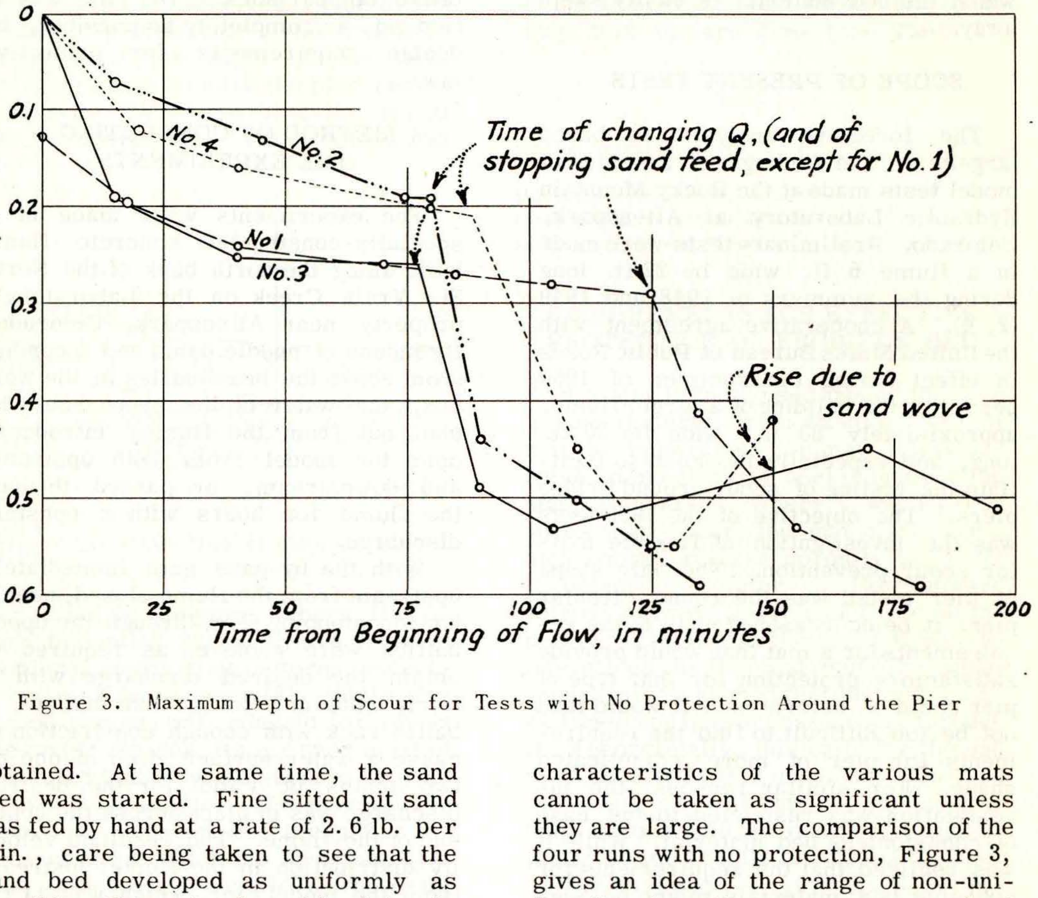
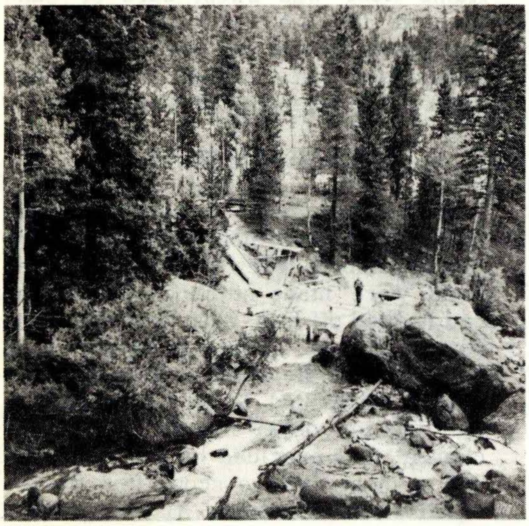
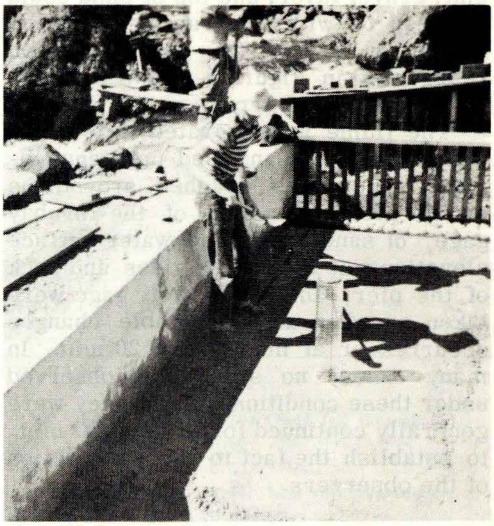


Figure 3. Maximum Depth of Scour for Tests with No Protection Around the Pier

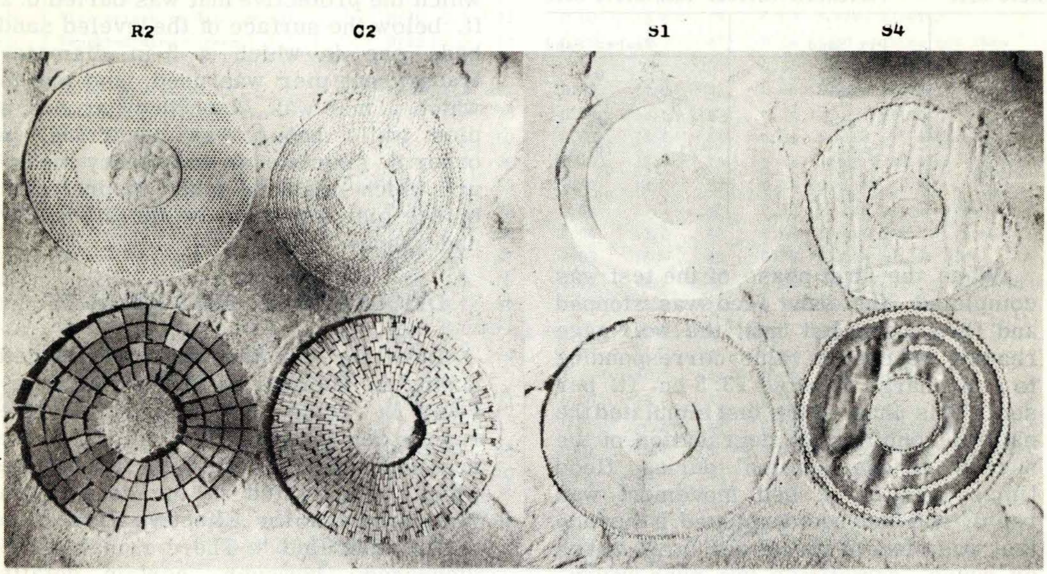
The method of observing scour depths next to the pier deserves especial attention. The transparent pier was graduated in tenths and hundredths of feet. By looking straight down the pier at a mirror held at 45 deg. to the



View of the flume from across the North St. Vrain Creek.



Leveling the sand bed preparatory to starting test.



Some of the types of mats tested

- R2 - Perforated rubber mat
- C2 - Link-chain mat with every adjacent link joined
- S1 - 16-mesh wire screen (on upstream rubber apron)
- S4 - 7-mesh weighted cloth
- B1 - Loose-jointed block mat
- B2 - Tight-jointed block mat
- S2 - 16-mesh wire screen, weighted
- S5n - Weighted 16-mesh plastic screen with neoprene apron attached under upstream portion

Figure 4.

vertical, the elevations of water surface, mat, gravel layer, and top of sand could be read to within a fraction of a hundredth of a foot (2). A photograph reproduced in Figure 5 shows readings reflected in the mirror.

The flume was operated at low discharge with pit-sand feed until equilibrium scour was reached around the bridge pier. Readings of the forebay gage, of sand, mat, and water surface elevations at the front, sides and back of the pier, and of the weir gage were taken as often as appreciable changes occurred or at most every 20 min. In many cases, no scour was observed under these conditions; if so, they were generally continued for at least 30 min. to establish the fact to the satisfaction of the observers.

TABLE 2

Sieve Size	Percentage Coarser than Sieve Size	
	Pit Sand	Washed Sand
No. 8	1	0
16	17	2
30	41	23
50	68	78
100	78	99
200	86	99

When the first phase of the test was completed, the sand feed was stopped and flow increased until the weir gage reading reached a value corresponding to a discharge of about 13. 5 cu. ft. per sec. This phase of the test simulated the natural condition of degradation of the narrow bridge section during flood times. Rate of bed movement was rapid, and the bed developed a surface that was smooth except for large waves or dunes, sometimes two such waves, but more often one. The waves were as high as 0. 25 ft. , and while their crests were usually perpendicular to the axis of the flume, occasionally one would be at an angle of as much as 30 deg. with the perpendicular. The passage of such a wave provided the most severe test of a protective device. A few mats survived this test without any evidence of incipient failure, whereupon the discharge was further increased and maintained at a still higher value until the flume floor was swept bare of sand opposite the pier or until it became necessary to end the test in order to investigate more closely the mechanism of the beginning of failure.

SPECIAL TESTS

In addition to the series of experiments made according to the procedure just described, a few tests of the better mats were made starting with a sand bed leveled off 6 in. deep over the flume bottom proper. These tests were then conducted in the same way as the previously described tests. By virtue of the smaller depth for the same discharge, they provided higher velocities and a more severe scour test for the equilibrium condition. Also, a greater depth was available for degradation.

Other special tests included one in which the protective mat was buried 0. 2 ft. below the surface of the leveled sand bed, one in which a 3-in. diameter transparent pier was used, and one in which a mat was "launched" around a pier while scour was occurring in order to simulate an emergency measure which might be taken to protect a bridge pier known to be threatened by underscour.

DISCUSSION OF TEST RESULTS

Data for all the tests performed during the summer of 1950 are summarized in Table 3. In general, the results demonstrated the validity of the requirements for effective protection which were stated in the section on "Requirements for Effective Protection of Erodible Bed." There remain to be discussed, however, certain details of the test results, including especially the materials of construction and methods of fabrication and installation of the mats which were found to function most satisfactorily.

It should first be noted that the use of any mat that had reasonable weight, perviousness, and flexibility gave considerable protection from scour. The materials of some of the mats - weighted cloth or plastic - are obviously

TABLE 3

SUMMARY OF DATA FOR TESTS MADE DURING SUMMER OF 1950

During first part of test, sand was fed at the rate of 2.6 pounds per minute. No sand was fed during second part of test. See Appendix for more detailed information.

Designation	TYPE OF PROTECTION ON STREAM BED AROUND PIER	FIRST PART OF TEST				SECOND PART OF TEST			
		Date	Q	Time	Deepest Scour at Pier	Q	Time	Deepest Scour at Pier	Remarks
			cfs	m	ft	cfs	m	ft	
	TESTS WHICH WERE STARTED WITH 4-INCH SAND BED								
1	No protection	8/9	5.7	125	0.30	(13.2)	(55)	(0.60)	(Sand fed throughout)
2	No protection	8/15	5.7	77	0.20	13.2	50	0.60	
3	No protection	8/17	5.5	72	0.26	13.7	30	0.53	
						13.7	88	0.51	Sand wave passing
4	No protection	9/4.	5.5	82	0.19	13.7	37	0.64	
G1	Coarse gravel rip-rap	8/10	5.5	60	0.00	(13.2)	(128)	(0.20)	(Sand fed throughout)
						(15.4)	(28)	(0.30)	Gravel washing away
G2	Coarse gravel on fine gravel	8/29	5.4	62	0.00	13.8	52	0.00	Gravel washing away
S1g	Wire screen on fine gravel	8/16	5.5	76	0.00	13.8	9	0.02	Screen buckled
S2	Weighted wire screen	8/12	5.9	81	0.09	14.1	47	0.24	Sand washing out thru
							120	0.23	channels under screen
S2g	S2 on fine gravel	8/14	5.7	182	0.00	14.0	30	0.00	Sudden washout; buckled
S3	Weighted plastic screen	9/1	5.6	38	0.04	13.6	9	0.14	ditto
S4g	Wtd. cloth mesh on fine gravel	9/2	5.4	60	0.00	13.9	64	0.11	Washed out upstream
S5n	Wtd. plastic with neoprene apron	9/4	5.4	38	(0.13)	13.9	76	0.14	Scour 0.12 when "launched"
R1	Solid rubber mat 1/8 in. thick	8/28	5.6	62	0.00	14.0	22	0.18	Buckled
R1g	R1 on fine gravel	8/28	5.6	32	0.01	13.9	40	0.13	Washed out upstream
R2	Perforated rubber mat	8/29	5.5	58	0.00	13.6	40	0.40	Tipped down in front
R2g	R2 on fine gravel	8/31	5.6	37	0.00	13.9	45	0.28	Washed out at side
B1	Loose-jointed block mat	8/15	5.5	60	0.02	12.9	43	0.28	Sand washed up thru joints
B1g	B1 on coarse gravel	8/16	5.7	62	0.00	13.3	176	0.32	Some gravel washed out
B1sg	B1 on S1 on fine gravel	8/21	Run during annual meeting - no data						Gravel washed out
B2	Tight-jointed block mat	8/30	5.3	94	0.00	13.7	129	0.28	Sand out from under mat
						16.8	118	0.32	next to pier
B2r	B2 on rubber apron	8/31	5.3	31	0.00	13.6	57	0.20	
						16.0	142	0.25	Mat bridging gap
C1	Link-chain mat	8/22	5.9	58	0.02	13.7	68	0.32	Bridging small gap under
C1g	C1 on fine gravel	8/22	5.6	62	0.00	13.5	65	0.00	edge
						14.8	141	0.00	Gravel escaping
C3r	C1 completely linked, on apron	9/1	5.4	16	0.00	13.9	51	0.20	Apron leaked flow
CX	9 in. Link-chain around 3 in. pier	9/5	5.2	32	0.00	13.9	51	0.15	Sudden wash-out
	TESTS WHICH WERE STARTED WITH 6-INCH SAND BED								
B2	Tight-jointed block mat	9/5	5.5	34	0.00	13.9	232	0.32	Cap under mat 0.11
C2g	Partially-linked C3 on fine gravel	8/24	5.6	42	0.00	14.0	125	0.00	
						14.0	3	0.15	Sudden wash-out
C3g	C3 buried 0.2 ft.	8/25	5.8	34	0.20	13.4	187	0.20	
						16.7	77	0.20	washed out upstream
						19.4	97	0.79	Edge exposed:

Eighteen-inch diameter mats around 6-inch diameter plastic pier for all tests except CX. The flume was approximately eighty inches wide, and the depth of flow on 4-inch bed at beginning of test was one foot.

unsuitable for permanent protection, though some comparable type of prototype construction might be developed which would prove valuable for emergency use.

Mats which seem to offer the greatest possibilities for economical long-time use are the link-chain and tight-jointed block mats (4) (see Figs. 4 and 5). The chain mat, in the prototype, might consist of worn tire chains fastened together link by link with steel rings, pickled to remove rust, and then hot-dip galvanized. Or, since small size interlocking areal ring meshes have been made by machine, it may be presumed possible to make a mesh of rings an inch or more in diameter by machine. There is an advantage in keeping the interstices small, and this is probably the reason for the superiority of the tight-jointed block mat, B2, over the loose-jointed block mat, B1. The latter was quite similar to the reinforced concrete articulated mats used in protecting Mississippi River levees, but was made by a different method, being cast at one time with partitions separating the blocks that could be removed after soaking in water. It had the same fatal defect as the articulated mats; in order to have the required flexibility and perviousness, the joints have to be wide, permitting concentration of upward currents and easy escape of bed material.

The tight-jointed block, which gave much better protection might be fabricated without excessive cost, and if corrosion-resistant materials were used, might have long life.

Although several mats were found that greatly inhibited scour, it was also found that by the expedient of installing a layer of gravel under a heavy pervious, flexible mat, scour could be completely prevented. In tests C1g and C2g no scour was measurable after flows had passed which would have dug scour holes 0.6 ft. or more deep with no protection, and perhaps 0.2 ft. deep with one of the better mats in place. Only when the general bed level had scoured down so deep that the edge of the chain mat was unable to follow down any further, did the gravel wash out, (see Fig. 5). In each case the test was then stopped, since the degree of protection provided by the chain mat without the gravel underlayer was known from previous tests.

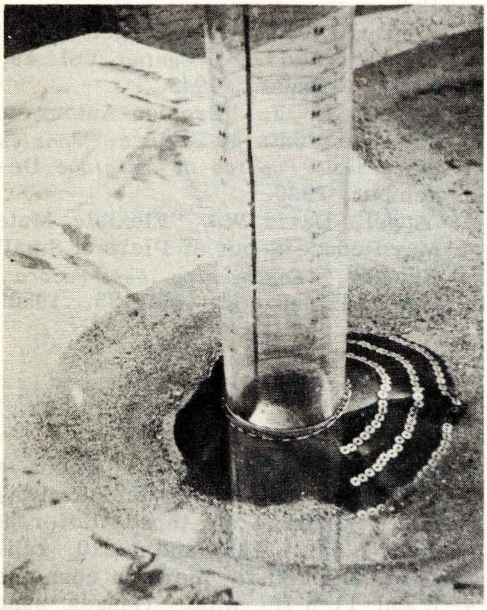
In one of the two tests made with gravel alone (no mat) coarse gravel was underlain with fine gravel. In the other, coarse gravel was used alone. The erosion protection provided by the two sizes of gravel in layers was superior, as was expected from experiences of the United States Bureau of Reclamation, from whence the suggestion originated. At the model scale, the two gravel layers must have functioned as a fairly effective reverse filter. Comparable prototype construction would probably require more layers.

One idea for providing protection was to reduce the downward flow in the stagnation zone by making the upstream portion of the mat impervious. A comparison of the results of tests B2 with B2r and C1 with C3r shows that this device did have some effectiveness. That it was not more effective may have been due to the lack of a watertight seal between the mat and the pier, at which juncture the pressure is highest. Downward flow at points where the rubber apron did not make close contact with the pier was observed in these tests.

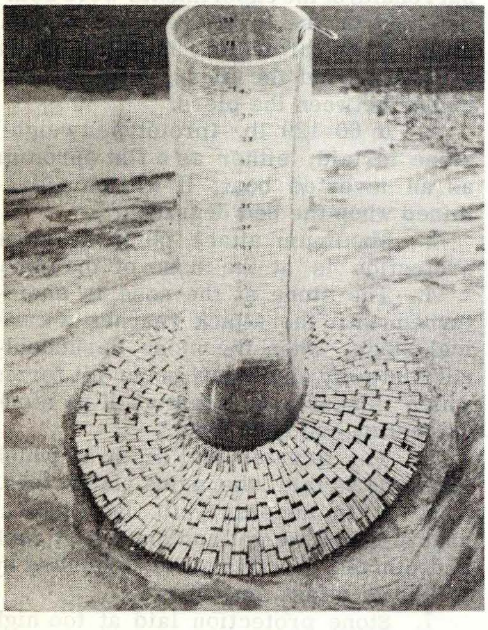
A special test with a 3-in. pier revealed that under different conditions the scour spiral may be larger in proportion and perhaps stronger, necessitating a larger diameter mat for complete protection.

SUGGESTIONS FOR FURTHER STUDY

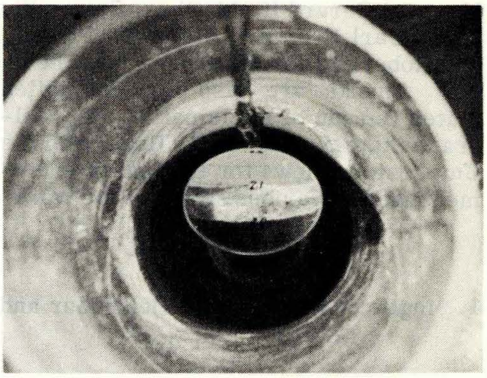
It would seem desirable to study methods of construction of full-size mats, and try out one or two on piers of a bridge over some wide river with an erodible bed. A systematic investigation of the various factors affecting the size and strength of the scour spiral, with the goal of determining the necessary size of mat or riprap protection, should also be worthwhile, as it would provide information of basic importance.



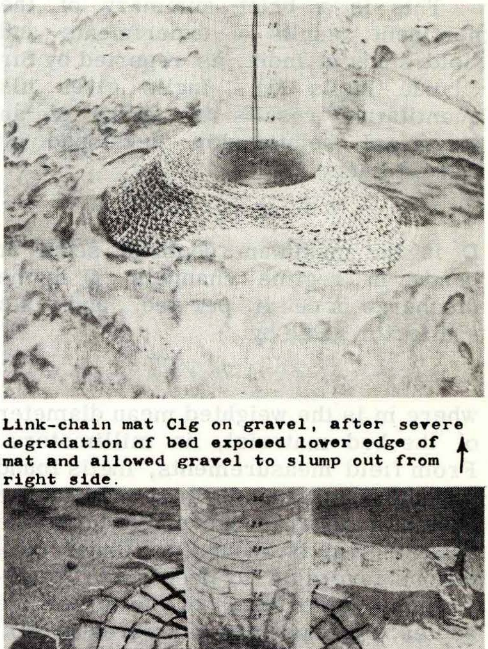
Weighted plastic screen S5n with neoprene collar under upstream portion. Unsymmetrical sand wave has just passed pier. ↗



Tight-jointed block mat B2, after general bed level has eroded down six inches. →



View of screen, sand bed, and pier graduations, as reflected in mirror.



Link-chain mat C1g on gravel, after severe degradation of bed exposed lower edge of mat and allowed gravel to slump out from right side. ↑

Loose-jointed block mat B1g at end of test. ←

Figure 5. The direction of flow is shown by the arrows with the captions.

ACKNOWLEDGMENTS

The stimulating suggestions of Messrs. Gerard H. Matthes, Emory W. Lane, Carl F. Izzard, Ralph W. Powell, and Robert Sailer have been most helpful. Thanks are also due the United States Bureau of Reclamation, the Colorado State A. and M. College, and the University of Iowa for the loan of equipment used in various stages of the work.

REFERENCES

1. Inglis, Claude, "The Behaviour and Control of Rivers and Canals," Central Waterpower Irrigation and Navigation Station, Poona, India, 1949.
2. Posey, C. J., "Why Bridges Fail in Floods," *Civil Engineering*, Vol. 19, p. 94, February, 1949.
3. Tison, L. J. "Erosion Autour de Piles de Ponts en Riviere," *Annales des Travaux Publics de Belgique*, December, 1940.
4. Appel, David W., "Flexible Mats May Reduce Scour at Piers of Small Bridges," *Engineering News-Record*, Vol. 144, p. 43, May 25, 1950.

APPENDIX

This is a brief summary of the pertinent results of experiments and field study in India, as reported by Sir Claude Inglis (1). Inglis gives his quantitative results in terms of an empirical relationship developed by Gerald Lacey:

$$D = .47\ (Q/_f)^{1/3}$$

D is the maximum depth of scour at bends in regime channels, Q is the discharge in cu. ft. per sec., and f is a slit factor given by

$$f = 1.76\ \sqrt{m}$$

where m is the weighted mean diameter of the bed material, in millimeters. From field measurements, Inglis found that the maximum depth of scour at the nose of railway bridge piers due to the scour spiral is about 2D. Under conditions favorable to deep scour downstream from bridges, due to turbulence eddies, the depth may be as great as 4D. (None of the R. M. H. L. tests showed deep scour downstream; presumably this applies when the bed material is cohesive.)

Lacey is said to have stated recently that f is not a factor in the depth of scour downstream from rigid structures. However, Inglis states that the work at Poona indicates that f is a factor and that $f^{1/3}$ is about right.

Model studies of scour around the pier of the Hardinge Bridge over the Ganges River were made at Poona in 1938 at the request of the Railway Board. Models of three different scales, 1/65, 1/105, and 1/210, represented the 180-ft. piers in channels 4, 8 and 11.5 ft. wide. Ganges sand with a mean diameter of 0.29 mm. was used, and also Nala sand. The principal results of the experiments were summarized in the following conclusions:

1. If no protection is laid, scour occurs around the piers, with the bed higher between the piers.
2. If 60-129 lb. (prototype weight) stone is laid, either as a flat apron or as an inverted boat, it will be undermined when the bed degrades.
3. Maximum attack on loose stone protection is at the nose of the pier.
4. The stone at the nose is undisturbed until the attack reaches a critical stage, when the stone is suddenly carried away and a deep scour pit forms which is nearly as great as if no stone protection had been used.
5. The greater the depth at which the stone is laid, the more stable it is.
6. It is necessary to use stone of such size and weight and place it at such a depth that it will not be disturbed by the worst attack anticipated.
7. Stone protection laid at too high a level may cause deep scour downstream and thus lead to stone being depleted from the tail and consequent failure from downstream scour.

RESEARCH REPORTS *

Special papers and reports similar to those published in the Proceedings but extensive enough to warrant independent publication - Illustrated, paper binding.

No. 1-D	(1946 Supplement) Special Papers on the Pumping Action of Concrete Pavements (1946) 67 pp.	.60
No. 1-D	(1948 Supplement) A Survey of Pumping in Illinois (1948) 53 pp.	.60
No. 3-B	Progress Reports of Cooperative Research Projects on Joint Spacing (1945) 108 pp.	1.00
No. 4-B	Airport Runway Evaluation in Canada, by Dr. Norman W. McLeod (1947) 138 pp.	2.00
No. 4-B	(1948 Supplement) Airport Runway Evaluation in Canada, Part II, by Dr. Norman W. McLeod (1948) 83 pp.	1.50
No. 5-B	Skid Resistance Measurements on Virginia Pavements, by T. E. Shelburne and R. L. Sheppe (1948) 30 pp.	.45
No. 6-B	Surface Drainage of Highways (1948) 32 pp	.45
No. 7-B	Symposium: Investigation of the Design and Control of Asphalt Paving Mixtures and Their Role in the Structural Design of Flexible Pavements (1949) 115 pp.	1.80
No. 8-F	Prevention of Moisture Loss in Soil Cement with Bituminous Materials (1949) 38 pp.	.60
No. 9-A	Time and Gasoline Consumption in Motor Truck Operation as Affected by the Weight and Power of Vehicles and the Rise and Fall in Highways (1950) 80 pp.	.90
No. 10-D	Committee Report and Manual of Recommended Testing Procedures on Load Carrying Capacity of Roads as Affected by Frost Action (1950) 18 pp	.45
No. 11-B	Surface Drainage (1950) 57 pp.	.90
No. 12-F	Stress Distribution in a Homogeneous Soil (1951) 38 pp	.60
No. 13-B	Scour Around Bridges (1951) 26 pp.	.45

---

*Research Reports not listed on this page are out of print and not available.

NATIONAL RESEARCH COUNCIL

The National Academy of Sciences is a private organization of eminent American Scientists, chartered under a special act of Congress in 1863 to "investigate, examine, experiment, and report on any subject of science or art." The Academy maintains the National Research Council as its operating agency.

The Council, organized with the cooperation of the scientific and technical societies of America, enjoys the voluntary services of more than 2600 scientists making up over 400 standing committees, boards, and panels in all fields of the natural sciences; its membership includes representatives of business and industry. The Council provides advisory and administrative services for research, and attempts to stimulate and coordinate research effort.

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

The National Research Council operates through eight divisions covering fundamental and applied natural sciences, as well as matters of international relations in scientific research. The Division of Engineering and Industrial Research is concerned with the stimulation and correlation of research in a wide variety of fields in engineering and the applied sciences.

EXECUTIVE COMMITTEE - C. RICHARD SODERBERG, Chairman; WM. R. HAINSWORTH, Vice Chairman; FREDERICK M. FEIKER, T. H. MacDONALD, PAUL D. FOOTE.

EXECUTIVE SECRETARY - LOUIS JORDAN.

HIGHWAY RESEARCH BOARD

The Highway Research Board is organized under the auspices of the Division of Engineering and Industrial Research of the National Research Council. Its purpose is to provide a national clearing house for highway research activities and information. The membership consists of 42 technical, educational, industrial, and governmental organizations of national scope. Associates of the Board are firms, corporations, and individuals who are interested in highway research and who desire to further its work.

The purposes of the Board are: "To encourage research and to provide a national clearing house and correlation service for research activities and information on highway administration and technology, by means of: (1) a forum for presentation and discussion of research papers and reports; (2) committees to suggest and plan research work and to correlate and evaluate results; (3) dissemination of useful information and (4) liaison and cooperative services."