NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 5

SCOUR AT BRIDGE WATERWAYS

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **5**

SCOUR AT BRIDGE WATERWAYS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

SUBJECT CLASSIFICATIONS:
- HIGHWAY DRAINAGE
- BRIDGE DESIGN
- CONSTRUCTION
- MAINTENANCE, GENERAL
- EXPLORATION-CLASSIFICATION (SOILS)
- FOUNDATIONS (SOILS)

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1970

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition to these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP Synthesis 5

Project 20-5 FY '68
ISBN 0-309-01899-4
L. C. Card No. 77-608742

Price: $2.40

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the Federal Highway Administration. Individual fiscal agreements are executed annually by the Academy-Research Council, the Federal Highway Administration, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, nor of the individual states participating in the Program.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

(See last pages for list of published titles and prices)

PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Highway Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

Included with this document is a return card by which reader reaction is invited. The knowledge gained therefrom will be directed toward improvement of future issues in light of the express needs of the potential users. Further follow-up will be made to determine the usefulness of the syntheses in highway practice and to effect updating as appropriate.

FOREWORD

By Staff

Highway Research Board

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information is often fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem is frequently not brought to bear on its solution, costly research findings may go unused, valuable experience may be overlooked, and due consideration not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Highway Research Board as the research agency, has the objective of synthesizing and reporting on highway practices—a synthesis being defined as a composition or combination of separate parts or elements so as to form a whole. Reports from this endeavor constitute a new NCHRP series that collects and assembles the various forms of information into single, concise documents pertaining to specific highway problems or sets of closely related problems. This fifth report of this series treats the problem of scour around bridge foundation structures. It will be of special interest to bridge design, construction, and maintenance engineers, as well as soils engineers, hydrology and hydraulics specialists, and geologists.

The erosive action of running water in streams, resulting in the carrying away of material from around bridge piers and abutments, has long plagued highway department engineers. Each agency having the responsibility for the design, construction and maintenance of bridges crossing waterways knows of the damage that can be caused by scour of materials supporting the bridge foundations. Bridge maintenance and replacement costs due to scour have been reported to run to millions of dollars. Although most agencies are concerned with this problem, only a few seem to have adopted the known hydraulic and hydrologic concepts for predicting scour depth. Much of the current-day design continues to be by rule of thumb or engineering judgment. Because highway personnel are responsible for the full range of problems surrounding bridges crossing waterways, the Highway Research Board has attempted in this project to set down those solutions found to be most practical to minimize the problem. The report includes recommendations for design procedures to minimize detrimental scour effects, recommendations for construction controls, and corrective maintenance measures that can be taken.

To develop this synthesis in a comprehensive manner and to insure inclusion of most significant knowledge, the Board analyzed available information—for example, current practices, plans, specifications, manuals, and research recommendations—assembled from the knowledge of highway departments, toll road agencies, and other agencies responsible for highway and street design, construction, and maintenance. An extensive survey of more than 100 organizations was undertaken in 1969 to determine practices that are currently in use. Furthermore, a thorough literature search of pertinent publications was made and interviews were held with knowledgeable highway personnel. A topic advisory panel of persons knowledgeable in the subject area was established to guide the researchers in organizing and evaluating the collected data, and for reviewing the final synthesis report.

As a follow-up, the Board will evaluate carefully the effectiveness of the synthesis after it has been in the hands of its users for a period of time. Meanwhile, the search for better methods is a continuing activity and should not be diminished. Hopefully, an early updating of this document will be made to reflect improvements that may be discovered through research or practice.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Highway Research Board under the supervision of Paul E. Irick, Assistant Director for Special Projects. The Principal Investigator responsible for conduct of the synthesis was Thomas L. Copas, Special Projects Engineer.

Special appreciation is expressed to Gay D. Jones, Chief Soils and Foundation Engineer, Howard, Needles, Tammen & Bergendoff, who, as special consultant to the Advisory Panel, was responsible for the collection of data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Advisory Panel, consisting of Murray L. Corry, Hydraulics Engineer, Hydraulics Branch, Office of Engineering and Operations, Federal Highway Administration; Lester A. Herr, Deputy Chief, Bridge Division, Office of Engineering and Operations, Federal Highway Administration; Emmett M. Laursen, Professor of Civil Engineering, University of Arizona; James L. Norris, Assistant Chief Engineer (Bridges), North Carolina State Highway Commission; Sidney L. Poleynard, Assistant Chief Location and Design Engineer, Louisiana Department of Highways; and Travis W. Smith, Assistant Materials and Research Engineer, California Division of Highways.

John W. Guinnee, Engineer of Soils, Geology, and Foundations, and L. F. Spaine, Engineer of Design, both of the Highway Research Board, assisted the Special Projects staff and the Advisory Panel.

Information on current practice and ongoing research was provided by numerous highway agencies, railroads, universities, consultants, and contractors. Their cooperation and assistance was most helpful.

SCOUR AT BRIDGE WATERWAYS

SUMMARY

Each agency having responsibility for bridges crossing waterways is concerned with the adequacy of the structure foundation. Problems that are the result of unanticipated scour at piers and abutments can have a major effect on the service life of the bridge. Because of the cost involved in the loss of a structure it is wise to estimate the possibility of scour and weigh the risks during the design and construction phases.

Scour is defined as the displacement of stream bed material by stream or tidal currents. It may occur naturally or be the result of channel constriction or changes in the flow pattern. Flood stages are not a necessary requirement, but the greatest scour, except under unusual circumstances, occurs during the largest floods.

Two types of scour are (1) *the clear-water case* where material is removed from the scour hole and not replaced, and (2) *the sediment-transporting case* where the scour hole is continuously supplied with material from the sediment load carried on the stream bed. The designer should be cognizant of which type will occur because the scour prediction procedures differ for the two cases.

The possibility of either degradation, the gradual lowering of the stream bed, or aggradation, the slow deposition of material in the channel, should be a design, construction, and maintenance consideration. The accumulation of drift and other debris may cause aggradation that reduces the waterway opening, thus increasing the chance and degree of scour.

There are choices available to the designer that may have an appreciable effect on the scour potential at a particular site. Waterway opening, stream alignment, pier size, and pier alignment are the more obvious choices.

A survey of state highway departments, railroads, contractors, government agencies, consulting engineers, and research organizations indicates that scour is more serious in areas containing alluvial material. Scour may also be a problem where flash floods occur.

The survey indicated that practicing design engineers consider hydraulic and hydrologic information, engineering geology, and historical data, with considerable weight given to the performance of adjacent structures when estimating scour potential. Several methods are used for computing the maximum flow at the structure site. Storm frequencies of 50 and 100 years, or the largest flood of record, are commonly used in design. Methods or procedures for predicting scour vary, with "engineering judgment" being more widely used than the more refined estimating methods.

Current design techniques in use to provide scour protection at bridge waterways include:

1. Provide sufficient opening to limit average stream velocity to 4 to 6 ft per sec.

2. Select the alignment, shape, and location of piers and abutments.
3. Make an estimate of the probable scour depth.
4. Secure proper embedment of the foundation.
5. Utilize supplementary design features such as riprap, sheet piling, longer piles, special stream bed protection, and improved channel.
6. Restrict the use of massive handrails, utility lines suspended under structures, and flood plain construction or quarrying activity.

Construction activity can increase the scour potential at both new and adjacent existing structures. Channel changes, removal of stream bed materials for embankments or aggregates, large cofferdams, and temporary ramps into the stream can produce unanticipated scour.

Most major structures are inspected for scour annually; however, some agencies require an inspection of scour-susceptible structures after major floods. Weighted lines, rods, and occasionally echo-sounding devices are used to check for scour holes. Both conventional and "wet-suit" divers are used to make substructure inspections. However, it should be recognized that the scour hole refills as the flood recedes. Accordingly, the depth of scour observed after a flood may not be indicative of the maximum scour that occurred during the flood.

Routine inspection and minor scour repair is normally handled by the agency maintenance unit. More extensive or major repairs may require contractor assistance. Corrective measures that were reported for scour damage are:

1. Riprap protection.
2. Sheet-pile cofferdams and cut-off walls.
3. Spur dikes or jetties to divert stream flow.
4. Sheet-pile dam downstream.
5. Underpinning with grout or concrete.
6. Raising bridge to increase opening.
7. Relocation of replacement bridge.
8. Use of junk automobile bodies for local control.

The estimation of scour at a bridge waterway involves both the determination of what could happen to the stream in the natural course of events and the effect of the bridge and embankment. This requires three predictions: (1) the magnitude of the flood, (2) the pattern of the flow, and (3) the depth of scour. This synthesis is concerned with the depth of scour. Two examples are developed to illustrate the "designer's dilemma" with the use of the formal prediction methods that are available.

Specific recommendations for planning any waterway crossing are listed for preliminary investigation, hydrologic investigation, hydraulic investigation, and geologic investigation. The suggested general order of work is:

1. Design the bridge in the usual manner for the normal, nominal flood frequency.
2. Estimate the scour.
3. Estimate the scour for a rare, or the maximum likely, flood.
4. Estimate the cost of foundations for normal and rare flood conditions and determine the annual risk.
5. Maintain accurate records and files that will permit review of the cost and risk data.

A first priority for research is the collection of field measurements, including the investigation of bridge failures caused by scour. Research into reliable methods of predicting rare floods also deserves high priority. The erodibility of cohesive soils and soft rock should also be studied.

A discussion of the relationship of scour and risk is included in Appendix C.

CHAPTER ONE

INTRODUCTION

Millions of motorists annually use Interstate Highways, toll facilities, and state, city and county roads to cross rivers, streams, bays and tidal inlets in safety and comfort. To maintain this flow of traffic is the responsibility of city, state, county and federal agencies. The railroads also depend on the safe crossing of streams for the transport of passengers and freight. All of these operations are dependent on the adequacy of the various bridge elements, including the foundation structure and the supporting material.

This synthesis is concerned with the prediction of and design for scour in the material supporting the foundations of the bridge rather than with the total design of the bridge proper. Scour, as defined in *ASCE Manual No. 43,* is "The erosive action of running water in streams, in excavating and carrying away material from the bed and banks. Scour may occur in both earth and solid rock material." Scour is frequently the activity that removes a bridge from service, resulting in road closures, loss of life, travel delays, and major expenditures for repair and replacement. For the 15-year period, 1955-1969, the Bureau of Public Roads reports that an average of $22.6 million per year of federal emergency relief funds were used in financing repairs and reconstruction of roads and bridges on the Federal-aid highway systems and on roads and trails in the federal domain. A comparable expenditure of state and local funds can be assumed. A significant portion of this can be attributed directly to the result of scour at bridge waterways (Fig. 1).

Scour is a natural phenomenon that occurs primarily in alluvial streams, but it is by no means limited to such streams, because the removal of channel bed and bank material by the scouring process can be found on any stream. In coastal areas, the scour induced by tidal flow or waves can be an important factor in the design and construction of bridge foundations.

Scour that may occur at a bridge waterway can be categorized as follows: (1) the scour that would occur in the stream with or without a bridge crossing, (2) the scour that may occur generally at the bridge waterway because the flow is contracted by the bridge crossing, and (3) the local scour that occurs because of the distortion of the flow pattern in the immediate vicinity of the bridge piers and abutments. Because the scour pattern is a result of the flow pattern and the variation in sediment-transport capacity from point to point in the stream, these categories are not completely independent. Separating them conceptually, however, is useful in understanding the total problem.

Several different kinds of behavior that are characteristic of the stream itself may be involved in scour. There may be a displacement of the stream channel, as in the migration of a meander, the shift of the thalweg of a braided stream, or a chute cutoff. Usually scour at one location is accompanied by deposition at another, and over a long period the stream channel may work back and forth over the same area. Similarly, scour and fill will occur during a flood, because a river is a series of contractions and expansions. Each contraction or expansion may be of the stream channel width, of the floodplain flow leaving and returning to the channel, or of the stream lines within the channel, as in bends and crossings. In subcritical flow, which is the condition in most rivers, the contractions scour during the rising hydrograph and fill during the recession, whereas the expansions fill during the rise and scour during the fall.

Behavior of this nature might be considered the fluctuation about a mean. It can be assessed by observation of the river in its natural state, together with soils and engineering geology investigations of the valley sediments.

Degradation may occur naturally, with the stream as the geological agent for erosion, or it may be man-caused due to stream straightening, the result of augmentation of the stream flow, or the reduction of sediment supplied to a reach, as by a dam. The stream bed may lower considerably due to degradation; therefore, the likelihood of this type of action should be assessed in the hydraulic design of any bridge. The vulnerability of existing bridges also should be checked when river control works are planned that could result in degradation.

The opposite type of action, aggradation, in which there is deposition in the river channel, should also be assessed, because it may create problems. The obvious problem is the raising of the water surface because of the rise in the stream bed in the long reach. This would not seem to be a

Figure 1. Bridge failure due to scour during flood.

scour problem; however, the rise in water surface could cause the hangup of drift on the lower members of the bridge, restricting the waterway area under the bridge and increasing the capacity of the flow locally to transport sediment (Fig. 2). The resulting local scour could be greater than the general aggradation. Deposition in the river channel can also result in a greater percentage of the flood flow encroaching on the floodplain, which could result in added local scour at the abutments.

The embankment fills of the highway crossing often will create a severe contraction of the river in flood. The floodplain flow must then move laterally to the bridge opening. Where this lateral movement takes place is very important. If the flow returns to the channel largely in a reach of some length upstream from the bridge, there will be general scour over the entire waterway opening. If, however, the flow returns along the embankment there will be severe scour at the abutment and possibly out to the first or second pier, with the general scour taking place downstream from the bridge. To what extent a specific site will tend toward one extreme or the other depends on the topography and vegetation at the site. The flow will seek the easiest route, and the scour potential of this behavior can only be assessed by first predicting the flow pattern for the conditions that will prevail during the life of the bridge.

Finally, there is the local scour that occurs at the pier and abutments because these structures, by their presence, produce a change in the flow pattern. The geometry of the structure and the flow pattern are the determinants of this scour. Figure 3 shows the probable local scour action at a circular shaft.

Similar descriptions of the local scour process are given by most investigators. Neill (*43*)* describes the phenomenon as follows:

> Flow approaching and dividing around the nose of the pier, in addition to being curved in plan, acquires a downward or diving component in elevation, for reasons that can be explained theoretically. As it straightens out by reversing plan curvature along the sides and around the tail of the pier, it acquires a rising component. The diving flow at the nose causes scour, and the rising flow downstream removes most of the scoured material and heaps it up at the tail. As the hole develops, a spiral roller forms inside it around the nose, throwing the scoured material out of the hole, to be swept away by the main stream.

Local scour occurs when the capacity of the flow to remove or transport the bed material is greater than the rate at which replacement materials are supplied. This suggests a basis for categorizing local scour by considering the sediment-transport condition into the scour area. Clear-water

* References are to entries in the "Selected Bibliography" (Appendix A).

Figure 2. Drift accumulation increases scour potential.

scour occurs with no transport or when the material supplied moves more readily than the material scoured; for example, fine sand supplied to a gravel-armored scour hole. This is in contrast to the scour that occurs with general sediment transport. During active scour the difference between the case of sediment supply and the case of no supply is primarily a difference in the rate of scour. At the limit, however, when capacity equals supply, there is a very fundamental difference between the two cases.

For the clear-water case, limiting scour is reached when the capacity for transport out of the scour hole is zero. This condition is reached when the flow is no longer competent to move the bed material, or when the boundary shear becomes equal to the critical tractive force of the bed material. The boundary shear is a function of the velocity of flow; the geometry of the situation, including the depth of scour; and the roughness characteristics of the boundary surface. The critical tractive force is a function of the characteristics of the bed material (size of sand, cohesion of clay, etc.). Therefore, the depth of clear-water scour can be expected to be a function of the geometry, the velocity of flow, and the sediment size (or other comparable characteristics). Examples of clear-water scour problems would be relief bridges and bridges with riprap protection.

For the general sediment-transport case, the limiting scour is reached when the capacity for transport of sediment out of the scour hole becomes equal to the supply of sediment into the scour hole. Assuming that the geometry of the situation, including the depth of flow and the depth of scour, remains constant, a change in the average velocity of flow will result in a proportional change in velocity at every point and a similar change in boundary shear at every point. Therefore, the new capacity for transport out of the scour hole and the new rate at which sediment is supplied to the scour hole should differ from the old values by the same factor and will still be equal. The same argument holds for a change of sediment size; therefore, neither velocity of flow nor sediment size should affect the depth of scour in this case. Qualifications to this conclusion are inherent in the implicit assumptions made in the argument: (1) the Reynolds number should be high enough so there is no appreciable change in flow pattern (this is even true of most laboratory models); (2) the Froude number should not be so high that there is an appreciable change in the water surface configuration, and thus in the flow pattern; (3) the boundary shear should be sufficiently greater than the critical tractive force that the change in particle shear in the scour hole and in the approach flow results in similar changes in sediment transport; and (4) the mode of sediment movement should not change (i.e., it should remain either largely bed load or suspended load). Because the

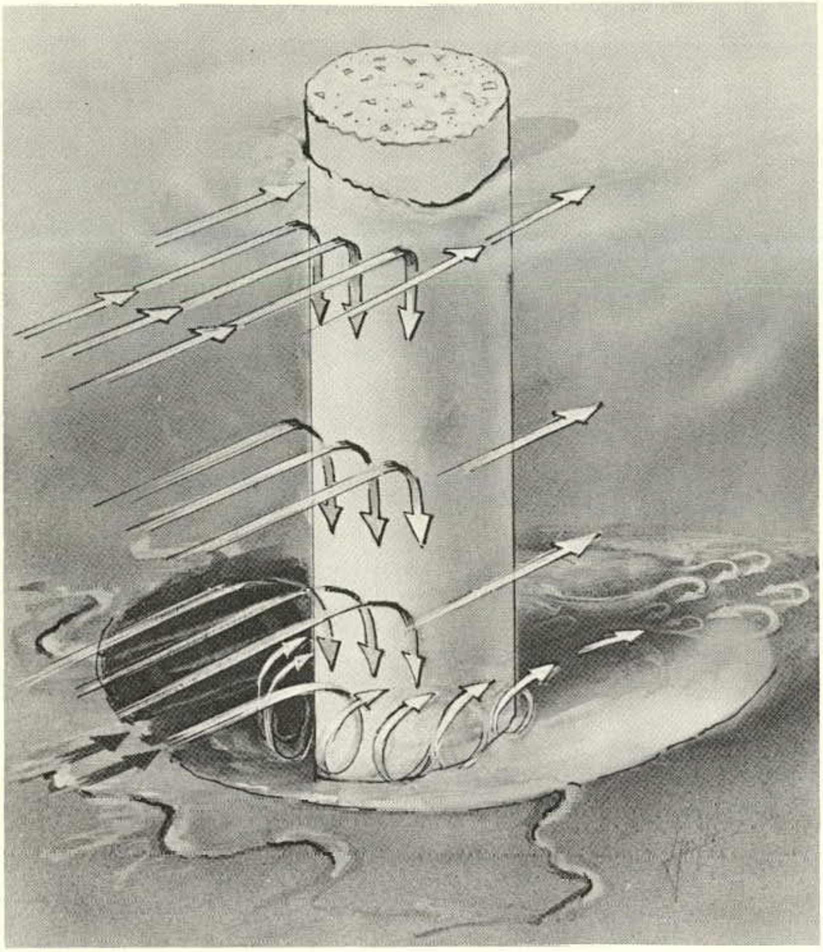


Figure 3. Scour at circular shaft.

sediment being considered is the bed material that must be scoured out, this fourth qualification is not as restrictive as it might appear; the presence of a suspended load of sediment finer than found in appreciable quantity in the bed is immaterial. It should be noted, especially in the case of scour by sediment-transporting flow, that a river in flood changes geometry and flow pattern as well as velocity.

Soils and engineering geology investigations of the bridge site are required for good foundation design. If the scope of these investigations is somewhat broadened, evidence of natural stream scour in the past is likely to be uncovered. An indication from boring data of the extent of degradation (or aggradation), of stream shifting, of potholes, or of contraction scour, could provide a base for estimating the scour potential at a site. It should be recognized, however, that it will usually be very difficult to associate the past evidence of scour with the magnitude or frequency of flood.

The soil profile should be used to determine if a resistant layer exists that will inhibit the depth of scour, thereby making the problem one of clear-water scour. On the other hand there could be layers of scour-prone material that could "blow out" before the sediment supplied by the stream could replace the fine material in place.

In assessing the scour potential due to man-made causes —especially the bridge crossing and its foundations—three predictions are necessary: (1) the flood magnitude and frequency, (2) the flow pattern for each flood with the geometry of the given design(s), and (3) the resulting scour. None of these predictions can be made with satisfying confidence, yet they must be made, because scour will occur unless the stream bed is inerodible. If a scour prediction is not made explicitly, it is made implicitly in the design of the foundations.

Analysis of the scour potentiality of a design will naturally lead to consideration of alternate designs, hopefully costing less. A small pier will result in less scour, but may require more reinforcing than a large pier; there may be a choice between a non-aligned pier or a skewed bridge—or a pier designed to be parallel to the flow at the bottom and perpendicular to the bridge at the top. It should be noted that the embankment need not be designed for the same flood as the bridge. However, if the embankment is designed for overtopping or with a "fuseplug," its height cannot be increased later without determining the effect of the resulting flood pattern on the bridge foundations.

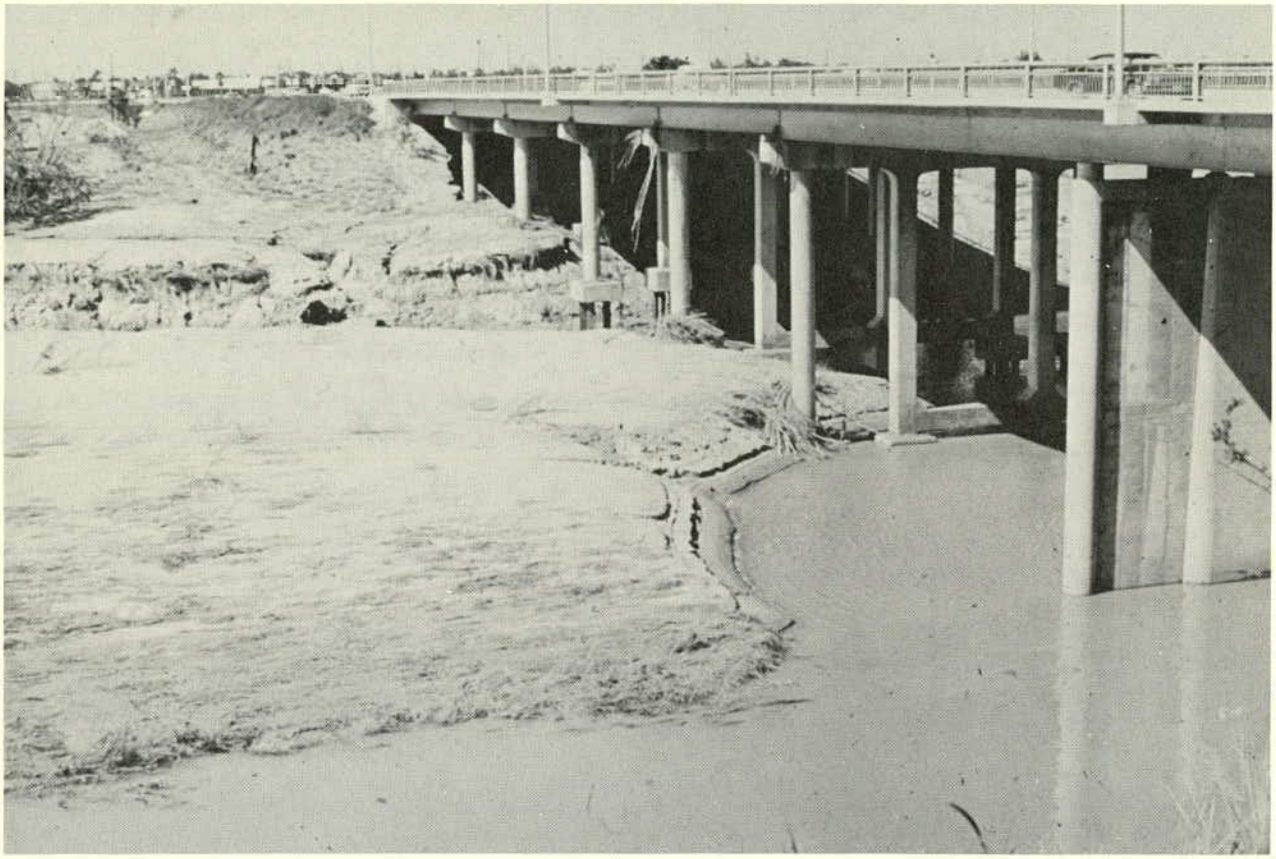


Figure 4. Highly erodible material at bridge site.

The scour of general interest to bridge designers and contractors is that which occurs during medium to major floods; therefore, the hydraulics and hydrology of the bridge site are of vital concern. Because stream bed materials differ, scour proceeds at variable rates dependent on the material involved. Consequently, the geology and foundation conditions of the bridge site are of great importance (Fig. 4).

There are many parts to the puzzle of assessing the scour potentiality of a bridge design. That many of these parts cannot be predicted, or estimated with a confidence as great as desirable, is just another engineering challenge.

CHAPTER TWO

PRESENT PRACTICE

SCOPE OF 1969 SURVEY

One of the primary considerations of this synthesis was the determination of current practice with regard to investigation, design, construction and maintenance of bridge structures whose foundations were subject to the effects of scour. An extensive survey, including written and oral interviews, was conducted in 1969 with many organizations having responsibility for design and maintenance of bridge structures (Appendix E). The representative nature of the survey is indicated by the following summary of contacts:

CATEGORY	CONTACTS	REPLIES
State highway departments	47	46
Railroads	21	19
Contractors	13	6
Government agencies	5	4
Consulting engineers	29	15
Research	21	13

The problem of scour at bridge structures is recognizably more serious in certain geographical areas. Areas containing considerable alluvial material adjacent to major rivers such as the Mississippi and Missouri, their tributaries, and certain coastal and glacial outwash areas will experience a considerable range of scour problems. The less humid western portion of the United States will expect serious scour problems at times of flash flooding, even though stream beds might be dry for much of the year. Streams in the West and Northwest having bedrock exposed at the surface may experience little or no trouble with scour yet have many bridge stability problems as a result of debris collection during flooding.

It is believed by virtue of contacts with state highway departments and railroads having extensive trackage over all portions of the United States, consulting engineers working for many widely scattered clients, and government agencies such as the Bureau of Reclamation, Bureau of Public Roads, and U.S. Army Corps of Engineers, that an adequate base was established to adjudge present practice in the United States. A list of the agencies responding to the 1969 survey is given in Appendix D.

DESIGN

In the design phase most state highway departments include some hydraulic, hydrologic, and engineering geology studies. Railroads rely principally on historical data available for a site. The Corps of Engineer districts, and consultants, depend primarily on the stream bed material encountered and the hydraulic characteristics of the flow cross-section. All agencies give due consideration to the performance of existing structures in the immediate area.

Stream Analysis

The primary topic covered in the 1969 survey questionnaire was scour and not hydrology; therefore, little was learned about the specific hydrologic techniques employed by the various agencies. Most agencies include some form of hydraulic review of the proposed site and several indicate that the responsibility for scour predictions rests with their hydraulic engineer. Several agencies indicate that they have no specialists in hydraulics, or soils and foundations, to provide assistance in scour-related problems.

In general, there appears to be good cooperation between agencies, with considerable emphasis being placed on hydrologic data or designs developed by the U.S. Army Corps of Engineers and the U.S. Geological Survey. This has frequently led to a design based on historical rather than projected events. The Water Resources Division of the U.S. Geological Survey is the major source of basic river stage data through its surface water records for each state. It has been responsible, in cooperation with state agencies, for a number of flood-frequency reports for individual states. These reports are helpful in establishing the design hydraulic load at a given site, and are widely accepted for that purpose. With these data, the majority of the states establish a design that will accommodate the desired flow at some relatively low average velocity.

Empirical formulas and methods used for flood prediction include, but are not limited to, the following:

1. Rational method.
2. Talbot formula.
3. Pettis formula.
4. Meyer formula.
5. Soil Conservation Service methods.
6. Potter index.
7. Locally derived formulas.

The rational method is not generally used for large watershed areas, whereas some of the other methods are used only for large watersheds. As a general rule, the method used is determined by local preference and experience. At this time no method of determining design discharges from large urban and developing areas has been widely accepted.

Although the determination of stream flow pattern characteristics at various stages is important, relatively few agencies indicate that this is included in their normal procedure. The manner of determining direction of flow during high river stages was not mentioned. A number of the agencies apparently consider their field inspection to be sufficient.

The division of flow between main channel and overbank sections was not mentioned, but it is undoubtedly considered by most agencies. This is particularly important with relief or overflow structures. The alignment of the piers with respect to the direction of flow is frequently, but not always, considered. In some cases, an enlarged opening is provided to make allowance for the use of piers normal to the bridge in spite of the angle of flow. The use of the scour hole to reduce backwater depth has been suggested, but the scour hole area infrequently seems to be considered a part of the waterway area through a bridge opening.

Scour Predictions

The agencies were asked, "To what extent is scouring around bridge piers and abutments a problem for structures in your jurisdiction?" Seventeen percent indicated that there was no problem, 63 percent indicated some problem, and 19 percent did not reply. This indicates that scour at bridge waterways, although not always a major problem, is nevertheless of frequent concern.

Generally, the currently available formulas and charts for predicting the extent of scour are not used. This is indicated by Table 1. It may be assumed that engineering judgment was exercised in all cases and this frequently included historical experience, subsurface investigations, site investigations, and hydrologic and hydraulic analyses.

In general, although most agencies undertake some form of stream analysis, only a few seem to be realistically con-

TABLE 1

RELATIVE USE DATA

REFERENCE OR PROCEDURE	1969 SURVEY INDICATES NUMBER USING
1. Engineering judgment	46
2. *Bull. No. 4,* Iowa Hwy. Res. Board (Laursen and Toch)	18
3. No predictions made	10
4. No reply to question	8
5. Limiting flow velocity (2-4 fps)	3
6. Laursen, E. M., "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.,* Vol. 86, Paper 2369 (Feb. 1960)	1
7. Blench, T.	1
8. Einstein, H. A.	1
9. Liu, H. K.	1
10. Garde, R. J.	1
11. Stiefel, R. C.	1
12. Corps of Engineers *ETL 1110-2-60*	1
13. Ontario Highway Dept., *Pub. RR 115*	1
14. Locally derived empirical formulas	1
15. Model studies	1

cerned with the hydraulic and hydrologic processes involved in the prediction of scour depth. Much of current-day design continues to be by rote or rule of thumb. Other than attempting to limit average velocities to some locally applicable maximum, no attempt is made to provide for shifting flow patterns and directions, or other less frequent hydraulic phenomena. Little mention is made of the need for reviewing channel designs for varying flood conditions. Model studies are rare.

Some progress is being made in the collaboration of the various disciplines concerned with the scour problem. Bridge design practice is gradually being altered to include a team approach of structural, hydraulics, and soils and foundation engineers.

The hydrologic history of a particular site or area is still considered one of the most important parameters in design. By implication, most agencies indicate that it is the only really trustworthy method. The hydrologic history of a site is generally reviewed to establish a design discharge. Some agencies set design frequencies with a 50-year return interval or maximum flood of record. One agency reported using a 100-year return interval as a check.

Present Trends in Design to Withstand Scour

The survey on present practice contained the question, "What techniques are used to insure maximum protection for bridge piers and abutments?" Although the replies varied in content and detail, the following fundamentals were evident and seem to be fairly well established in the minds of designers throughout the United States:

1. Provide waterway openings to limit average stream flow velocity to 4 to 6 ft per sec.

2. Select alignment, shape, and location of piers and abutments to minimize obstruction to stream flow and creation of turbulence.

3. Estimate maximum probable scour depth. Many of those interviewed recommended this, but gave no specific procedures for accomplishing it.

4. Secure proper embedment of foundations:
   (a) *Soil-bearing spread footing and caisson.*—Locate below anticipated depth of scour.
   (b) *Pile-supported footing.*—Take piling to bedrock or obtain substantial penetration in firm material (from 3 to 8 ft of cover between river bed and top of footing).

5. Use supplementary design features:
   (a) Riprap around substructure units and in adjoining channels, including graded filters.
   (b) Sheet-pile cofferdams used to facilitate construction left in place as permanent protection.
   (c) Extra length piling in erodible material.
   (d) Spur dikes at abutments.
   (e) Encasement of riprap with wire fabric.
   (f) Sheet-pile cutoffs at toe of embankment and in front of abutments.
   (g) Rock riprap cone at base of piers.
   (h) Massive toe on any abutment riprap to avoid undercutting.
   (i) Replacement of in-situ bed material with large stone not likely to be scoured to attempt limitation of local scour around piers.
   (j) Removal of natural obstacles in vicinity of bridge that are likely to disturb the flow.
   (k) Improvement of channels upstream and downstream to prevent concentration of flow to bridge substructure.
   (l) Encouragement of tree and vegetation growth at proper locations.
   (m) Timber mattresses covered with heavy riprap.
   (n) Embedment of all footings in the floodplain, with consideration that the deepest part of the

channel may shift back and forth over a cycle of many years.

6. Restrictions:
   (a) Prohibit use of solid handrails.
   (b) Prohibit utility pipes from being suspended beneath structures.
   (c) Whenever possible restrict floodplain construction, quarrying, dumping, or other activities to prevent creation of scour development potential.

SCOUR PROBLEM RELATED TO CONSTRUCTION

Continuing environmental changes demand periodic evaluation of river bed conditions for the old as well as the more recently completed structures. One environmental change concerns the topography of the watershed and the floodplain area. Land use, particularly the procurement of borrow material for embankments, or quarrying operations, causes drastic alterations to the topography. Although current construction specifications require borrow areas to be located away from the roadway or bridge project for aesthetic reasons, they are generally within 300 to 800 ft of the right-of-way. Development of upstream borrow areas this close to a bridge will often result in varying the flow pattern, which may affect the depth and extent of scour along embankments, abutments, and piers.

Removal of borrow material from the stream bed itself has the effect of concentrating the flow. If combined with a restriction of the channel this may often have considerable bearing on the scour potential at an existing bridge or one under construction. The hole made when borrowing may move upstream by headcutting, or downstream by trapping the material supplied and eroding downstream (Fig. 5).

Environmental changes involving degradation of streams through channel improvements, cutoffs, new dams, etc., affect scour potential. It is difficult, if not impossible, to obtain long-range commitments or policies from stream regulatory agencies. This is somewhat understandable and it would be unrealistic to expect any immediate improvement in cooperation. Nevertheless, realignment of streams, dredging for navigational improvements, and associated activities, has considerable effect on scour at existing bridges, not only along the stream being straightened or deepened, but on tributary streams where stream bed gradients and flow patterns are changed.

The 1969 survey on scour attempted to obtain current experience related to scour at cofferdams and sand islands. Very few comments were received. Although not stated in precise terms, it was quite clear that the owner is presently content to have the responsibility for all construction remain with the construction contractor.

SCOUR INSPECTION AND MONITORING

Determining the extent of scour at bridge foundations is generally limited to observations during periodic inspections. In-depth periodic inspection by specially trained personnel varies from one to five years, but inspection by maintenance personnel is more frequent, generally on a yearly basis. Most inspections are scheduled at times of normal stream flow, even though it is recognized that more meaningful scour depth determinations would be obtained during floods. High velocities, floating debris and murky water accompanying flood flows make inspection and monitoring at these times difficult and dangerous. Special inspections of bridges are usually conducted following major floods, with particular attention to scour. Bridges known to have problems with scour are inspected more frequently.

Soundings by weighted line, rod measurements, or other direct physical measurements are prevalent. Several agencies reported excellent results with electronic depth recorders, although one agency noted that use of hand sounding lines and/or electronic sounding devices has proved inaccurate with respect to determinations of the shape and volume of the scoured area. This was apparently based on the fact that actual replacement quantities had considerably overrun the estimated quantities based on the measured scour. Both conventional and wet-suit divers have been used. Concern was expressed over the reliability of the information reported by inspectors and divers.

MAINTENANCE

According to AASHO, maintenance is "the preservation and upkeep of a highway, including all of its elements, in as nearly as practicable its original as-constructed condition. . . ." This is the objective of the personnel comprising the maintenance groups as established within the various agencies.

Detection and Reporting of Scour

Scour and scour-related problems usually are first detected and reported by maintenance personnel. The survey, however, did not attempt to establish the qualifications of the maintenance personnel in recognizing the seriousness of scour and reporting to a higher administrative level. Many agencies have trained these people in the detection, reporting, and repairing of scour problems in addition to their other, more routine duties. Some agencies placed those responsibilities with other divisions of the agency. Practically all agencies appear to rely heavily on the maintenance personnel in handling "scour problems."

Corrective measures ranging from minor, routine, or "normal" maintenance to actual reconstruction are performed by maintenance personnel. There is no clear definition as to what constitutes "normal maintenance," yet this often enters the decision as to whether repairs are to be performed internally, or externally by formal construction contract. Contractual procedure in one agency required that bids be received from at least three bidders for all work involving more than $500. Practically all agencies are organized so that on "major" problems—again not defined—the work is done with external forces, wherein construction plans and specifications are prepared, and bids taken, or the price negotiated.

Priority for maintenance due to scour problems is determined on the basis of the importance of the structure, the volume of traffic, the degree and type of repairs, and the extent of repairs required when a number of structures require simultaneous work.

Determination of desired corrective measures is predicted on the classification of the scour problem as one of a "minor or normal maintenance" or a "major" problem. Corrective action for the "normal maintenance" problems appears to be planned, designed and constructed by people at the maintenance operating level, although it can be assumed that the problems are known at higher administrative levels. In the case of "major" problems the decision as to type and extent of corrective measures most often rests with the Bridge Engineer, the Chief Engineer, or the Maintenance Engineer, acting independently or as a group. The estimated cost of corrective measures, in practically all cases, inherently determines the level of decision. The need for large sums of money obtainable only through budgetary action at a high administrative level would certainly involve decisions at that level. Corrective action requiring lesser funds, even though potentially as serious as the more expensive solutions, would normally be handled at the maintenance operating level.

Corrective Measures for In-Place Structures

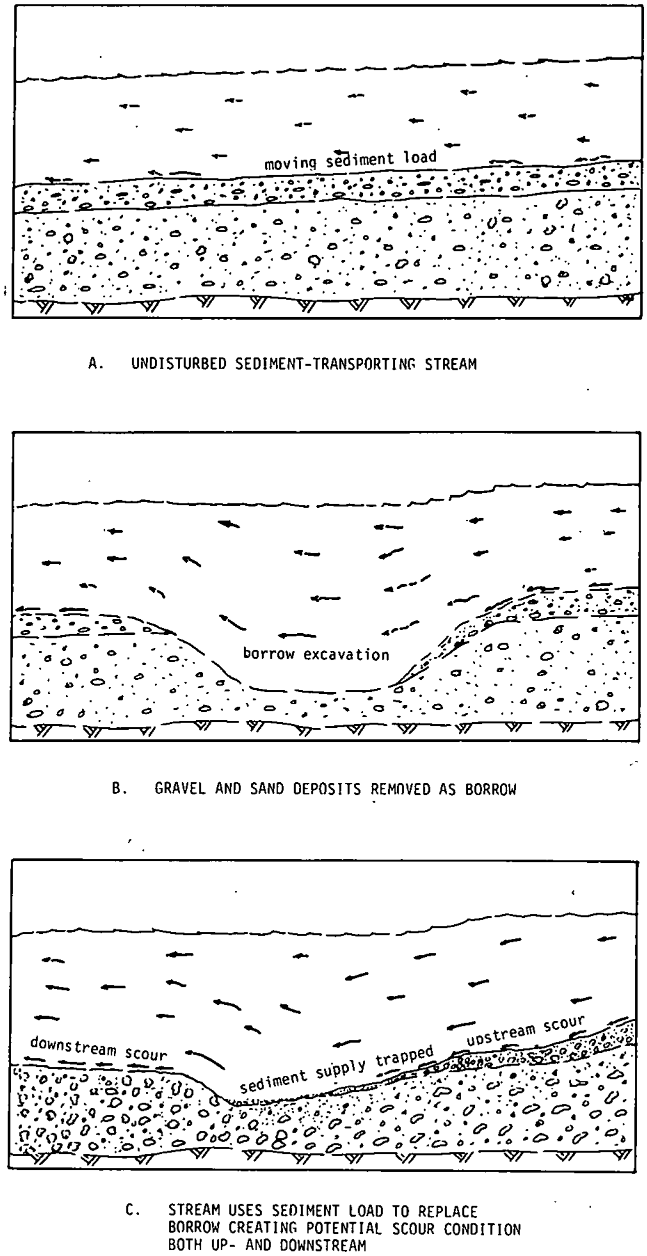
The extent of the repairs or new construction, whether described orally or by formal contract plans and specifications, is of necessity a "best guess" as to what might be required to correct a particular situation. In some instances it may be possible to evaluate the scour damage and needed repairs by actual visual and physical examination of the area "in the dry." Most often, the repairs are determined during the emergencies of flooding, or shortly thereafter, with depth soundings being the principal guide in assessing the seriousness of the problem. Regardless of the accuracy in definition of the problem, the following corrective measures are currently predominant:

1. Dumped rock riprap.
2. Sheet-pile cofferdam enclosures, and cutoff walls.
3. Spur dikes or jetties for partial diversion of the stream.
4. Sheet-pile dam downstream.
5. Underpinning with preplaced aggregate and pressure-injected cement, or cast-in-place concrete.
6. Raising or lengthening bridge to provide greater waterway opening.
7. Relocation of bridge if a new one is required.
8. Use of old automobile bodies for local control of adjacent bank erosion.

No attempt is made to differentiate between temporary and permanent repairs. They are all hopefully considered permanent, at least until such time as the need for new corrective measures becomes apparent.

Records of Scour

Once scour has been detected at a bridge structure the particular foundation units involved are usually monitored more frequently and the scour history is documented with photographs, hydrographic surveys, sounding data, internal departmental reports, and special reports by consultants.



A. UNDISTURBED SEDIMENT-TRANSPORTING STREAM

B. GRAVEL AND SAND DEPOSITS REMOVED AS BORROW

C. STREAM USES SEDIMENT LOAD TO REPLACE BORROW CREATING POTENTIAL SCOUR CONDITION BOTH UP- AND DOWNSTREAM

Figure 5. Stream bed disturbance.

Complete as-built records are maintained where corrective measures were extensive enough to require construction plans and specifications.

Although costs attributed to scour generally are not separated, some agencies do compile detailed records of bridge maintenance and replacement costs related to scour. For the nine agencies reporting dollar values, the approximate cost of bridge repairs and/or replacements due to stream scour within the past 15 years varied from $20,000 to "several million dollars."

CHAPTER THREE

METHODS OF ESTIMATING SCOUR

The estimation of scour at a bridge waterway involves both the determination of what could happen to the stream in the natural course of events and what could happen because the embankment and bridge are placed across the valley and stream. The first requires observation of the present state and the past history of the stream. Evidence of past scour may be quite clear, as when there is relatively thin alluvial fill on a residual soil, or quite ambiguous when the valley has been slowly aggrading for a long time. Assigning a probability of occurrence is usually difficult for natural stream scour predictions, but is probably not essential because this is usually the least scour to be expected.

As stated in Chapter One, evaluation of the effect of the bridge crossing requires three predictions: (1) the magnitude of the flood, (2) the pattern of flow, and (3) the depth of scour. This three-part evaluation separates the elements of such an over-all judgment and directs reason explicitly into the various factors determining the scour depth. Judgment is still required for each part.

For large streams the flood data can usually be obtained from U.S. Geological Survey records, and in many states regionalized flood magnitude-frequency studies are available. For small streams, there is under way in many states an active program of flood flow measurement that eventually should allow much better estimates of flood flow. Presently, some empirical method such as the rational formula, the BPR-Potter index, or the SCS method is customarily used.

The flow pattern must also be evaluated, especially the division of flow between floodplain and channel, and the angle of attack at the piers. At sites with complex geometry of topography and vegetation, engineering judgment is again required—especially when considering possible future conditions. The natural shifting of the stream channel can be a factor, as can also change in the use of the floodplain.

However, detailed examination of the twin problems of the prediction of (1) flood magnitudes, and (2) flow pattern are outside the scope of this synthesis. The subject topic is (3) prediction of depth of scour. Given the flood magnitude, the flow pattern, and the geometry of bridge and site, what depth of scour can be expected? A number of researchers have proposed different formulas that give different answers. Examples of some of the formulas and/or charts developed by researchers are given in Appendices B and C. To assist the engineer in selecting a formula, or formulas, a brief resume of the sources used by the researchers is included.

Even a cursory review of the formulas reveals that each is based on those factors which appeared to be most important to the research at hand. Which to use? Perhaps the best, and maybe the only, guide available to the practicing engineer is to compare the particular design situation with the circumstances under which a particular formula was derived. At the present time, new ideas and new applications of old ideas are the subject of research, with the result that the assurance of using the "right" formula is still illusive.

Examples 1 and 2 summarize the predicted or estimated depth of scour for the clear-water and sediment-transporting cases, respectively, according to the equations developed by these investigators.

EXAMPLE 1—CLEAR-WATER SCOUR

This illustrative example is a bridge crossing of a large estuary with only tidal currents to consider. The proposed bridge consists of a number of long spans that isolate the scour at each pier from the effect of adjacent piers or abutments. Bridge clearance is great enough to eliminate drift considerations and the climate does not permit the formation of ice. Therefore, this may be considered as an instance where local scour resulting from pier construction is the primary consideration.

Water depth is 69 ft, with an average velocity of flow (tidal current) of 2.0 ft per sec. The bed material is very fine to fine sand (mean size 0.1 mm), overlain by a thin silt layer. The pier is rectangular, 47 ft wide, and aligned with the flow. Sediment transport into the area is negligible. Predicted depths of scour are given in Table 2.

TABLE 2

PREDICTED DEPTH OF SCOUR FOR EXAMPLE NO. 1 * (CLEAR-WATER)

	PREDICTED DEPTH OF SCOUR (FT)	
EQUATION	D_s, FROM WATER SURFACE	d_s, FROM BED LEVEL
Ahmad ($K=2$)	54	no scour
Blench	63	no scour
Breusers		66
Chitale		no scour
Inglis-Poona	52	no scour
Inglis-Lacey	11	no scour
Larras		35
Laursen and Toch (I)		80
Laursen (II)		63
Laursen (III)		13
Neill		79
Shen (I)		15
Shen (II)		1.5

* See Appendix B for equations.

EXAMPLE 2—SEDIMENT-TRANSPORTING CASE

This illustrative example is taken from an actual case study in which the river is transporting a bed load. Only the local scour around the center pier of the five-span bridge is used for illustration. The stream is contained within high banks and the cross-section is almost trapezoidal (in fact could be considered rectangular). The bed material is a medium to coarse sand with a mean size of 0.5 mm. The piers are aligned with the flow, round nosed, and 6 ft 7 in. wide at the stream bed. The flood magnitude-frequency relation for the stream can be approximated by a straight line on log-probability paper. The stream characteristics for several possible floods are as follows:

RI (YR)	Q (CFS)	DEPTH (FT)	AREA (FT^2)	AVG. VEL. (FPS)
50	56,000	28.2	14,224	3.94
500	83,000	31.2	16,249	5.11
5000	120,000	35.1	18,802	6.39

Predicted depths of scour are given in Table 3.

TABLE 3

PREDICTED DEPTH OF SCOUR FOR EXAMPLE NO. 2 * (SEDIMENT-TRANSPORT)

EQUATION	PREDICTED DEPTH OF SCOUR, d_s, (FT) FOR A FLOOD FREQUENCY OF 50 YEARS	500 YEARS	5,000 YEARS
Ahmad ($K=1.5$)	6.3	13.1	20.4
Blench	0	1.6	4.9
Breusers	9.2	9.2	9.2
Chitale	7.3	13.0	19.4
Inglis-Poona	1.6	4.8	7.9
Inglis-Lacey	7.1	9.1	10.4
Larras	5.8	5.8	5.8
Laursen and Toch (I)	13.8	14.2	14.7
Laursen (II)	13.6	14.5	15.4
Neil	12.2	12.6	13.1
Shen (I)	5.5	6.5	7.5
Shen (II)	5.3	8.9	12.9

* See Appendix B for equations.

DISCUSSION

The completely different answers given by the prediction formulas in Tables 2 and 3 illustrate the designer's dilemma: Which is the "right" formula?, or is any one of them the "right" formula? Checking into the background of the formula and examining the variables considered in the equation can give some insight into its probable usefulness.

In Example 1, the "Indian" equations (Ahmad, Blench, Chitale, Inglis-Poona, and Inglis-Lacey) indicate that no scour would occur. These equations are based either on field experience of the rivers and canals in India or Pakistan or on model studies that attempted to simulate those rivers. The Inglis-Lacey equation is a simple statement that the depth of scour measured from the water surface is twice the regime depth. Because Example 1 is not a sediment-carrying regime river, the actual depth of flow is more than twice the regime depth; the equation thus is not applicable to this case of clear-water scour. Although the Hardinge Bridge laboratory experiments were run essentially as clear-water scour, the experiments were meant to simulate a regime river and were interpreted as such. The Inglis-Poona equation is based on the first set of these experiments and the Chitale equation includes a later series. Neither equation contains the sediment size as a factor, which makes them both suspect as clear-water scour equations. The Blench equation is based on the Inglis-Poona equation with the insertion of the regime depth as a factor, and thus contains the limitations of both. The Ahmad equation is based on both field and laboratory observations and is probably limited to regime river conditions; the size and shape of the pier is not a factor, except possibly through the choice of the coefficient, K.

The two Shen equations are for the maximum scour that occurs, presumably as the approach bed begins to move. Because the conditions of Example 1 are well below the critical tractive force for the bed material in the approach, the Shen equations would not seem to be applicable either.

Although the Neill equation is described as being for the maximum scour (which implies the incipient-motion limitation), it gives results very close to the first two Laursen equations (which are for the sediment-transporting case); either interpretation would make it inapplicable to Example 1. Similarly, the Larras and Breusers equations seem to be for the sediment-transporting or incipient-motion cases (neither include the sediment size or the velocity) and would be inapplicable.

This leaves the Laursen (III) equation as the only one that might be applicable, as it was designed for the clear-water case and seems to predict model results reasonably well. However, there is no field confirmation. The Reynolds-form Shen equation gives about the same prediction for Example 1, but this would appear to be coincidence; a change in sediment size would not change the scour prediction of the Shen equation but would that of the Laursen (III) equation.

In Example 2 the range of predicted scour depths is not as great as it is in Example 1, but still the range is sufficient to give the designer difficulty. All of the equations except those of Larras and Breusers show an increase in scour depth with the magnitude of the flood; some because of a change in velocity, some because of a change in depth. The Blench and Inglis-Lacey equations are of doubtful use because the depth of flow in this stream is not the Lacey regime depth.

The Ahmad, Chitale, Inglis-Poona, Shen (I), and Shen (II) equations all contain the velocity of flow, either explicitly or implicitly. Therefore, for the same depth of flow and geometry of pier but a different velocity (and slope or roughness) the scour prediction would be different. This goes to the heart of one of the controversies about scour—

in the sediment-transporting case does the velocity have a considerable or an inconsiderable effect on the depth of scour? The predictions of the Neill and the first two Laursen equations would not be changed by a change in velocity. Note that the predictions of these three equations are quite close. Note also that the increase in scour depth with magnitude of flood should not represent a great increase in construction cost.

Explicitly or implicitly, provision must be made for scour at bridge piers and abutments—because scour will take place if the conditions are right. The practice of determining a waterway opening based on some permissible average velocity and founding the piers and abutments at some depth based on experience is an implicit method of providing for scour. There are two weaknesses in this method. First, the average velocity is not the typical velocity of concern, because the flow pattern under the bridge is not one of a uniform velocity distribution: if there is scour, the flow pattern is very three-dimensional. Second, the usual experience is not good enough. The average annual flood is encountered routinely, but a 10-year flood is news and a 50-year flood is big news. Experience with rarer floods is highly unlikely and liable to be written off as being beyond any reasonable expectation. Yet to reduce the chance of occurrence in a nominal 25-year life to 5 percent requires consideration of the 500-year flood—well beyond ordinary experience.

Because so few field measurements of scour have been made, and those few leave something to be desired, the various methods of predicting scour cannot be checked against reality. *Therefore, it is quite impossible to build a feeling of confidence in any prediction method—or even to compare methods or set limits on the validity of methods.* However, a few comments are in order. The depth of scour is of the order of the width of the pier or the depth of the flow. The geometry of the pier or abutment will have some effect, with the angle of attack of the pier and the amount of flow around the abutment being the most important factors. There is a difference between clear-water scour and scour by sediment-transporting flow. Drift accumulation can alter the geometry of the pier or of the waterway opening.

Sorely needed are programs of field measurements: measurements at sites of simple geometry, measurements at sites of complex geometry, measurements in large rivers during moderately high flow, measurements during floods. Only as a result of field measurements can confidence be obtained in some prediction method that does a reasonably adequate job. Only in this way can the inadequacies of prediction methods be found; only in this way can an acceptable comprehensive prediction method be finally formulated. In the meantime, the best judgment of designers must be relied upon, aided by such analyses and empirical data as are available.

CHAPTER FOUR

RECOMMENDATIONS FOR DESIGN, CONSTRUCTION, AND MAINTENANCE INSPECTION

GENERAL DESIGN PROCEDURE

At present the procedures used to assess the potential for scour at and around the foundations of a bridge are somewhat vague. The expected depth of scour must always be implicit in the design of the foundations, and some organizations make scour predictions rather than simply including this element in the engineering judgment factor of the bridge and foundation design.

It is recommended that the scour problem be explicitly recognized and that scour predictions be made for the different possible floods and for alternate designs with the object of selecting the best design, balancing cost and risk.

In recent years the matter of cost versus risk, as concerned with design to accommodate for scour, has been discussed more freely. However, at present no general agreement exists among the various authorities and agencies as to the advisability or applicability of procedures. It is recommended that designers assist in the resolution of a proper approach to this consideration through the following general order of work:

1. Design the bridge in the usual manner for normal, nominal flood frequency.
2. Estimate the scour.
3. Estimate the scour for a rare, or the maximum likely, flood.
4. Estimate the cost of foundations for normal and rare flood conditions and determine the annual risk.
5. Maintain accurate records and files that will permit review of the cost and risk data.

HYDROLOGY AND HYDRAULICS

Prediction of scour involves the prediction of floods and flow patterns—both requiring the exercise of engineering judgment. Conservatism at this stage is essential.

For large watersheds, the regional studies of flood magnitude and frequency, such as those prepared by the U.S. Geological Survey in conjunction with various state and other federal agencies, can be used for frequent and even moderately rare floods. Determinations of rare floods by unit hydrograph procedures and rainfall information probably can be justified only for costly major crossings. Therefore, judgment must be used to extrapolate the flood magnitude-frequency relation. Regional studies of rare floods with magnitude (or discharge per square mile) plotted against area can be useful in the exercise of judgment.

For small watersheds it is necessary to go to some other procedure such as the rational method, the BPR-Potter index, or the SCS method. Which to use is a matter of individual, or organizational, judgment.

ENGINEERING GEOLOGY

An understanding of the geologic processes involved with the soil-bedrock development of the area is of particular importance with respect to scour.

Whenever possible a determined effort should be made, in both the preliminary and final design subsurface exploration program, to include provisions for appropriate drilling, sampling, and laboratory testing that will possibly aid in identification of the depth of previous scour, as well as provide information relative to scour potential of the foundation materials.

DESIGN INVESTIGATION

Specific steps involved in the planning of a crossing for any stream include:

Preliminary Investigation

1. High-water elevations, including critical flood elevations.
2. Flood flow patterns.
3. Cross-sections of the stream.
4. Stream meanders.
5. Vegetation.
6. Existing and proposed improvements.
7. Data on existing bridges upstream and downstream from the proposed crossing. Included would be types of bridges, span lengths, pier orientation and cross-sections, clearances, direction of flow, and scour history.
8. Comments on drift, ice, nature of stream bed, and bank stability.
9. High water from other streams.
10. Nearby reservoirs or flood control.

Hydrologic Investigation

1. Assemble flood records.
2. Determine drainage area above the proposed crossing.
3. Plot the flood-frequency curve.
4. Plot the stage (or depth)-discharge curve.
5. Plot the depth-frequency curve.
6. Determine the rare or maximum likely flood.

Hydraulic Investigation

1. Determine the design velocity and the permissible backwater.
2. Compute the backwater for various trial bridge lengths and approach embankments for various discharges. For an explanation of these computations see "Hydraulics of Bridge Waterways" (*11*).
3. Compute the mean velocities through the trial bridge lengths for various discharges.
4. Review the types and alignment of piers, and the need for spur dikes, channel changes, bank protection, or riprap.
5. Estimate the scour depths for the proposed bridge piers and abutments for various discharges.

Geologic Investigation

1. Study available contour and geologic maps.
2. Conduct geologic and field reconnaissance of the site.
3. Prepare a preliminary foundation plan.
4. Obtain borings.
5. Determine the depth to bedrock or adequate support.
6. Classify samples of undisturbed and disturbed cores.
7. Review the nature of the material and the filling, and possible oxidation.
8. Study for evidence of previous scour.
9. Assess the potential for scour.

By use of the data assembled, the designer can estimate the patterns and depths of flow at individual piers and abutments. Other important considerations are: character of the watershed, floodplain, and stream during the life of the structure; development of upstream and downstream areas; clearing of densely vegetated floodplains; shift of the thalweg of a braided stream; and construction of other bridges, or river works upstream.

SCOUR PREDICTION

Because satisfactory quantity and quality of field measurements of scour are not available for comparison, it is not possible to recommend a specific method for predicting scour. Judgment must be exercised in selection of a method, and in interpreting the resulting predictions.

Whichever method of prediction is used, the explicit consideration of scour should lead to a better design. If the predicted scour from one design is more than nominal, alternative designs with smaller piers, better shaped piers, riprap layers, etc., should naturally present themselves for consideration. Even the length of the bridge might be reconsidered. It should be noted that the embankment need not be designed for the same flood as the bridge, but if the embankment is designed to fail or overtop for large floods, thereby reducing the scour expected at the bridge foundation, it must not be raised in the future unless other measures are taken to secure the bridge.

Particular attention should be given to bridges located near the confluence with another stream. Here, a flood occurring on only one stream can result in a marked increase in the surface gradient. This will create higher velocities and may cause unanticipated scour.

EMBANKMENT DESIGNS TO MINIMIZE SCOUR

Embankment Scour

Embankments projecting into wide floodplains may produce a scour problem in two ways. First, the flow patterns of floodwaters create extreme concentration at the upstream corners of the embankment. In many cases this results in a serious scour potential at the abutment. Second, the embankment constricts the waterway opening, with a corresponding increase in flow, influencing scour at piers near the abutment.

Model studies conducted at the University of Iowa (*31, 36*) and at Colorado State University (*21*) yield an insight into the scour produced by embankment protrusions. Figure 6 shows the scour configuration expected for a normal embankment. Figure 7 shows the influence of embankments on scour at adjacent piers. The redirection of flow caused by the embankment may substantially increase the scour at certain pier types. Figures 6 and 7 merely indicate qualitative scour patterns. Unfortunately, neither theoretical nor empirical methods are presently available to gauge with confidence the scour configuration, or the depth to be expected under a given set of conditions. However, an understanding of the basic problem does provide a supplement to previous experience and engineering judgment in arriving at designs to minimize scour at embankments.

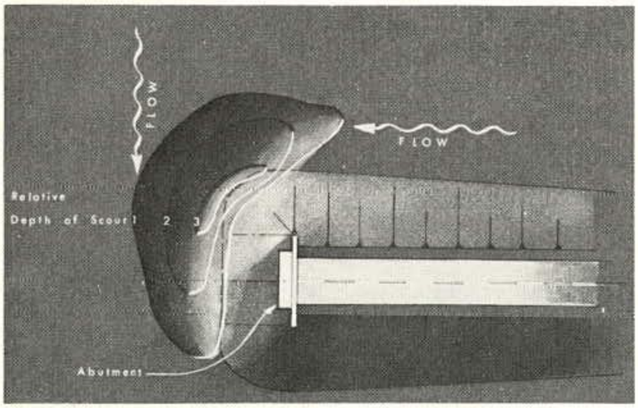


Figure 6. Scour at embankment.

It has been noted that clearings and borrow areas immediately upstream from an embankment markedly increase scour by increasing the lateral flow along the embankment. Such operations should be restricted or a study should be made to determine what additional protection might be needed.

Riprap Protection

For embankments where scour is expected, properly designed riprap affords protection against progressive erosion. In areas where stone is not available, sacked concrete may be used. Figure 8 shows the best arrangement of riprap on embankments and around adjacent piers.

An important consideration in this protective system is the size of riprap required. Intuitively the size of material that can be expected to remain in place must be directly related to the local flow velocity or boundary shear. Although experience may be the best guide in determining riprap size and gradation, some guidance may be gained from the Corps of Engineers' *Technical Letter No. 1110-2-60,* "Engineering and Design Criteria for Riprap Channel Protection"; the California Division of Highways publication, "Bank and Shore Protection"; and the Bureau of Public Roads' *Hydraulic Engineering Circular No. 11,* "Use of Riprap for Bank Protection" (*50*).

Sheet-Pile Toe Walls

Sheet-pile toe walls do not inhibit scour, but they do provide restraint and prevent erosion of the embankment section. Figure 9 indicates the scour pattern expected with this type of protection. Design calculations will establish the relation of scour depth and the degree of flexibility of sheet piling and the need for anchoring with deadmen, walls, etc., to provide an effective structural system.

Spur Dikes

Spur dikes projecting upstream from embankments seem to afford the optimum of protection both for the embankments and for the adjacent piers. The function of the spur dike is twofold. First, the flow pattern of floodwaters is

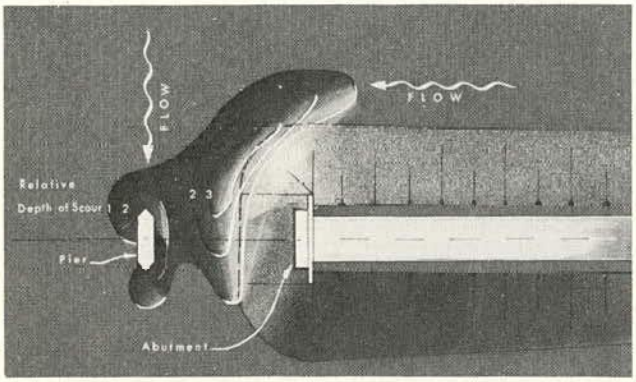


Figure 7. Scour at embankment and adjacent pier.

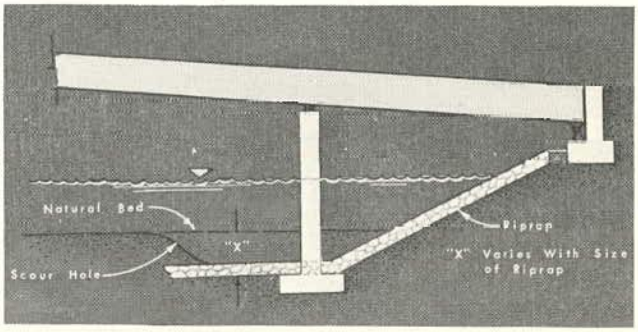


Figure 8. Riprap protection.

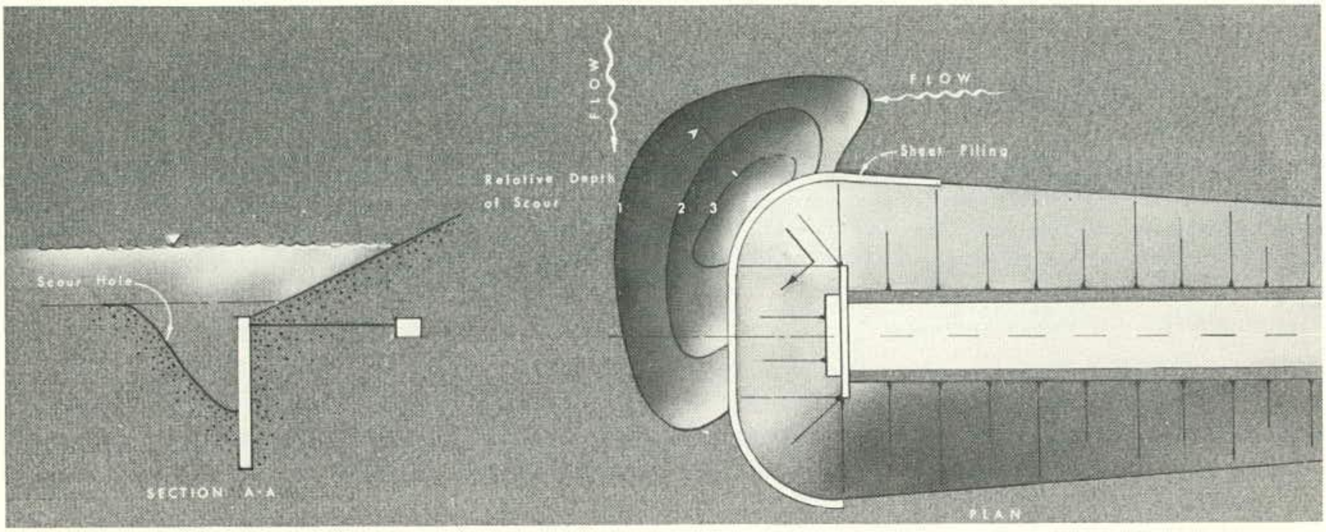


Figure 9. Sheet-pile embankment protection.

redirected to parallel the desired channel alignment and thus utilize the full bridge opening. Second, the scour hole developed is upstream from the bridge, minimizing scour at the embankment and the adjacent pier. The effectiveness of spur dikes is a function of the geometry of the roadway embankments, the flow on the floodplain, the distance to the bridge, the slope to the bridge, and the size of the bridge opening.

The scour pattern expected at spur dikes is shown in Figure 10. Details of dikes employed by the Mississippi State Highway Department are shown in Figure 11. This design has given satisfactory performance and has been credited with saving several bridges from destruction by scour action on embankments.

The Mississippi design requires a minimum length of 150 ft. Undoubtedly, individual sites can be adequately protected by shorter dikes, but some may require more length. Again, unfortunately, knowledge is not presently available to provide a definite design length criterion. Of all shapes tested, the elliptical shape with a 2.5 ratio of major to minor axes provides the best over-all result.

Installation of a spur dike does not eliminate scour, but lessens its degree and moves the scour hole upstream away from the abutment.

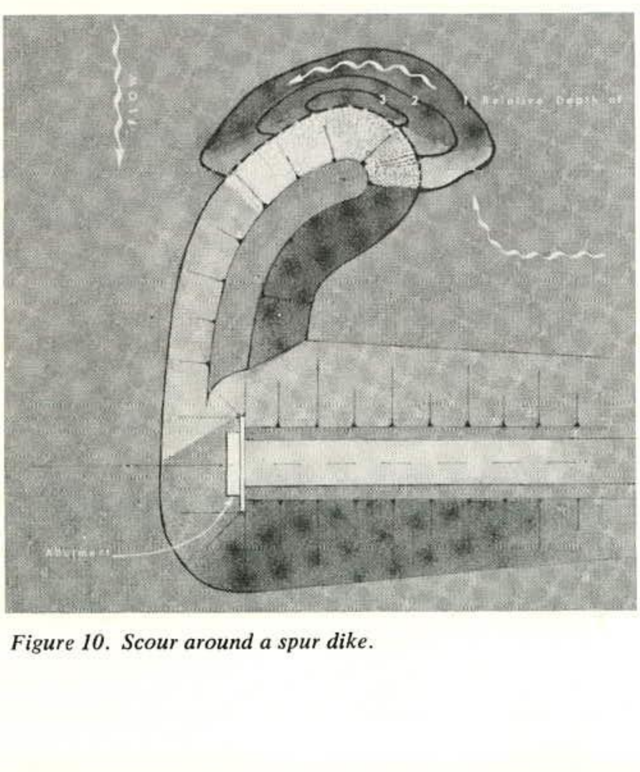


Figure 10. Scour around a spur dike.

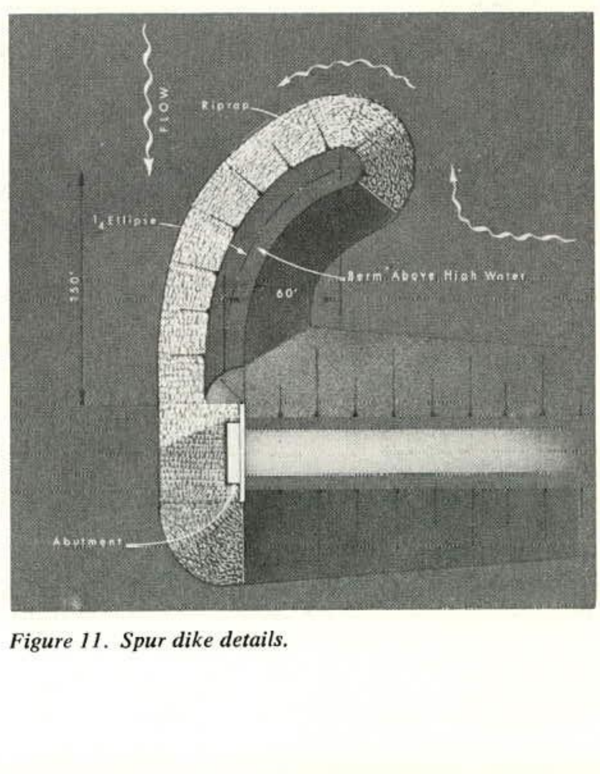


Figure 11. Spur dike details.

To be effective the dike must itself be protected from erosion. This protection, usually by riprap, is required at least on the upstream end of the dike. Previous comments on riprap protection for embankments apply similarly to spur dikes. If the adequacy of the abutment depends on the spur dike, the spur dike elevation must be above the design flood.

The Bureau of Public Roads' film "Spur Dikes" shows the action of stream flow at embankments.

PIER DESIGNS TO RESIST SCOUR

Scour Produced by Piers

Pier shafts projecting from the river bed alter the flow pattern of the passing water. The accompanying increase in velocity and turbulence can cause local scour in otherwise stable river beds, or increase the problem in already unstable situations. As noted and illustrated in Iowa Highway Research Board *Bulletin No. 4* (*36*), the size, shape, width, and alignment of pier shafts directly influence the depth and extent of scour. Although research has presented methods for estimating scour around shafts, it must be realized that the problem changes if scour can be anticipated to depths below the footings. However, the few experiments that have been made indicate that there may be compensating effects and the scour below a footing or pile cap is not much different from the scour around a deep shaft.

Drift accumulation can be considered as changing the shape and increasing the size of a pier. The quantity of drift expected will vary with the particular watershed.

Spread Footings in Soil

In alluvial material the top of the footings obviously should be placed well below the depth of any estimated scour. A criterion must be adopted as to the frequency of storm for which scour is predicted. This may be 50-, 500-, or 5,000-year frequency, or the maximum anticipated flood, depending on the importance and cost of the structure. Although it is possible to measure the economics of providing adequate protection for scour against the risk of failure, few bridge engineers will be commended for this approach when a bridge is lost.

On all but the least important structures, a very conservative approach is recommended when establishing foundation elevations in material subject to erosion, or when making decisions to use spread footings in lieu of piling. Figure 12 shows common sense practices relative to the design of spread footings where scour is anticipated.

Footings on Erodible Rock

Serious problems and failures have been encountered with piers founded on erodible shales, sandstones, or other rocks. Extreme caution should be exercised to establish footings at depths sufficient to prevent undermining and to protect the interface between the structure and its foundation. No method presently appears available for prediction of the severity of the problem of rock scour other than experience with other structures in the same area founded on similar material. Because scour is aggravated by increased velocities and turbulence produced by flow around the pier, any attempt to hydraulically streamline the pier base will obviously relieve potential problems (Fig. 13). Riprap placed around the base may also lessen scour.

Pile Foundations

Piling driven deep below the stream bed affords a degree of protection against failure by scour. This feature must not be taken for granted where scour is expected to depths considerably below the natural stream bed. A structural system must be provided to resist stream flow forces under the scoured condition and to provide stability. The piles need to be of sufficient length to support the structure after the scour has occurred. This structural system may utilize battered piles or the reserve bending strength usually available for frame action. Large precast piling, or filled pipe piles will, in many cases, improve the ability of a design to withstand scour at little or no increase in cost. Figure 14 shows typical pile foundation designs.

Drilled Shaft Foundations

In cases where severe scour is predicted, and piling cannot provide an adequate structural system or cannot be driven, drilled shafts or drilled piers offer a practical solution. The size and number of shafts can usually be varied to permit reasonable and economical designs for most conditions. Modern drilling equipment can excavate most gravels, clays, and relatively soft rock without difficulty. Drilled shafts or smaller cast-in-place piling also afford an economical solution where an erosion problem is expected in shales, sandstones, or other rocks. These materials may be readily drilled and foundation loads carried to depths well below any anticipated erosion. Figure 15 shows typical drilled shaft designs.

Sheet-Pile Protection

For pile footings where scour is anticipated below the footing level, some protection may be provided by sheet piling surrounding the footing. Where footings are constructed in cofferdams, protection or added insurance may be gained at little cost by providing anchorage to the footing or the seal and cutting off the piling above the footings. The footing should extend to intersect the scour hole that would be formed around a deep shaft and the sheet piling should project above the footing to provide a lip, which will act to arrest scour.

Designs utilizing filled sheet-pile shells also provide scour- and impact-resistant foundations. Additional strength and stability may be gained by grouting the fill. Figure 16 shows two designs with sheet-pile scour resistance.

Caissons

Caisson foundations are required where extreme scour or channel shifting is anticipated. In most cases where great depths of scour are predicted, open dredged caissons are economically competitive with the more modern drilled shaft designs with adequate resistance to lateral forces. Even though the width of caissons encourages scour to greater depths, stream flow forces seldom govern the design

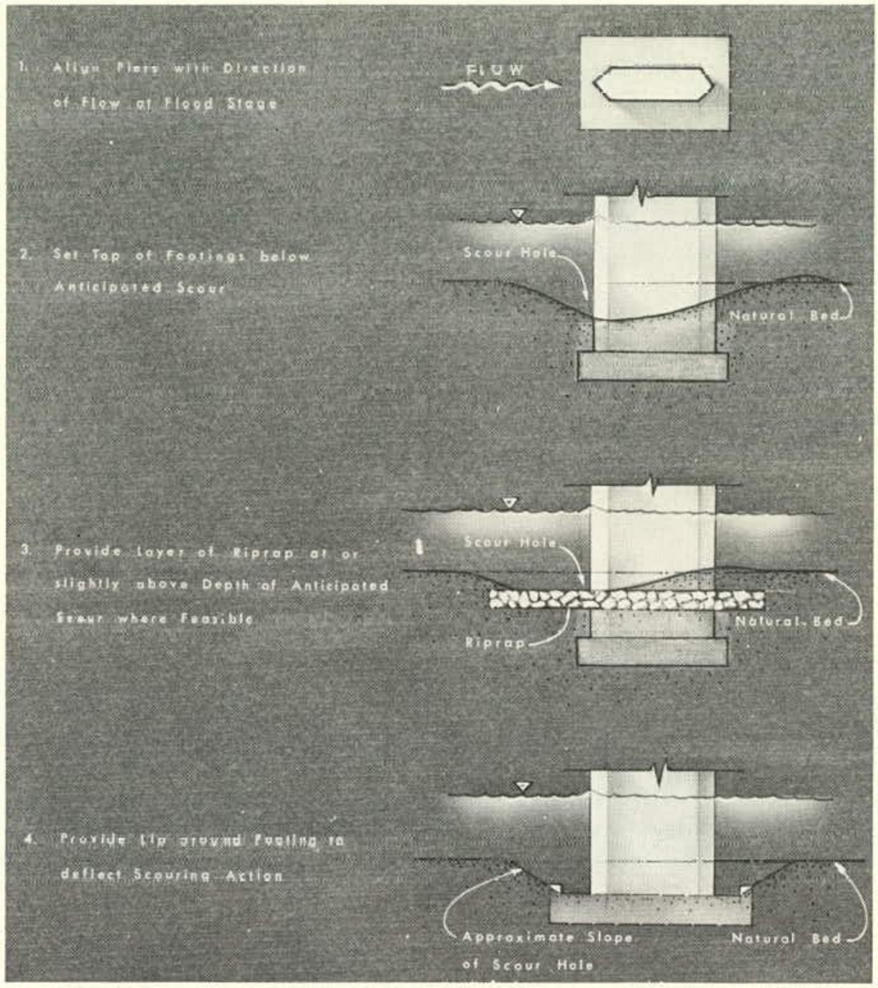


Figure 12. Recommended practice for spread footings.

because the dimensions must generally be large enough to provide stability during sinking.

In many cases timber or articulated concrete mattresses have been provided around caissons in main channels. If the mattress is required for scour control after construction, it is necessary to size the dumped rock (for timber mattresses) or concrete elements to withstand the design flood.

CONSTRUCTION

In many instances the development of scour potential is a gradual process; with adequate inspection and monitoring, scour problems can be anticipated somewhat. It is necessary that the scour process be watched closely in the formative stage, and that preventive or corrective measures be taken.

Construction Plans and Specifications

New construction and major corrective measures are performed according to detailed plans and standard construction specifications. These will be supplemented with special provisions or addenda as required to adequately describe the work to be accomplished. These documents should also include provisions for the prevention of unnecessary disturbance to the stream bed in the vicinity of existing or new foundation construction. Excessively large excavation for piers or pier repairs should be prohibited.

Special Precautions

The agency will normally acquire control over only enough property to provide for the new construction or corrective measures. Outside of this area the agency has little or no control over floodplain land use. Timbercutting, mining, earth borrow excavations, river dredging, certain types of farming, conservation and flood control uses, presence of bridges upstream, etc., may contribute significantly to the distribution of flow within the stream channel and the floodplain. This could have a great effect on the scour potential at a waterway crossing. In the design of new waterway crossings and when planning corrective measures for scour repair, it is imperative that the designer be reliably informed of any foreseeable occurrences that might be realized during the life of the structure.

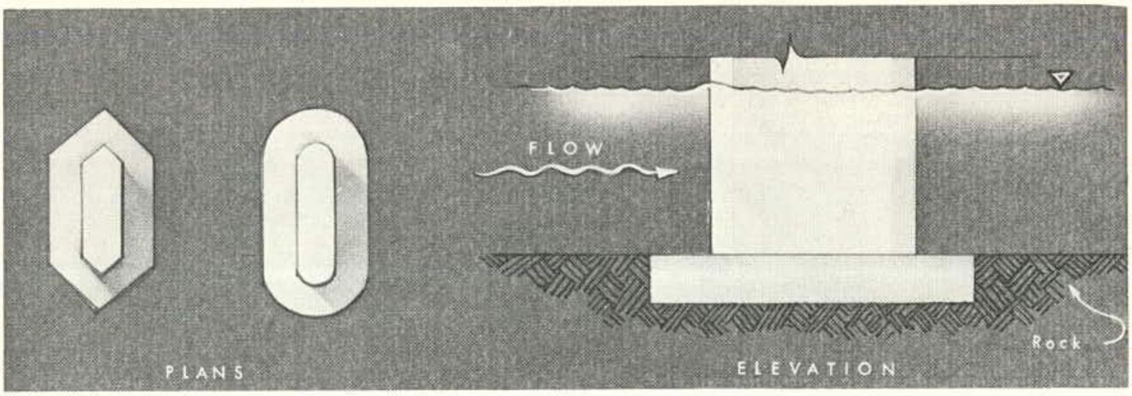


Figure 13. Pier base designs.

Observations and Reports

The conditions of piers and abutments, when scour preventive or corrective measures are initiated, should be documented in a special report, including photographs if possible. The extent of preparation required for the corrective treatment, and all reconstruction, should be documented in the as-built plans, including narrative reports, pile-driving records, etc. Where continued monitoring of the substructure unit is desired, complete instructions as to frequency, type of measurements, etc., should be explained to the responsible work unit. The AASHO *Manual for Maintenance Inspection of Bridges* provides guidance in these matters.

MAINTENANCE INSPECTION

Personnel

Bridge inspections are normally a team effort requiring specialists in substructure and superstructure. Inspection for scour and evaluation of its effects should be made only by those qualified in the analysis and design of bridge foundations.

Frequency of Inspection

The frequency of inspection will vary with organizational policy and with the susceptibility of individual bridge sites to scour. It is desirable that inspections for scour be made

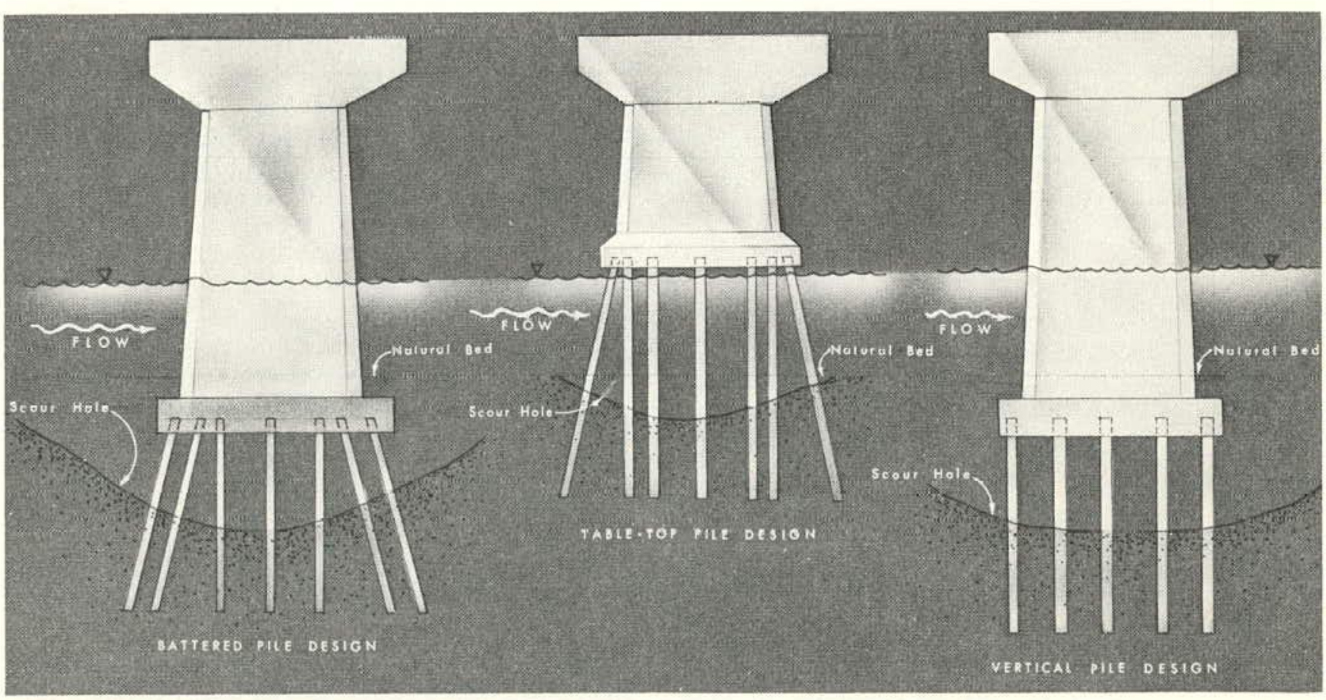


Figure 14. Pile foundation designs.

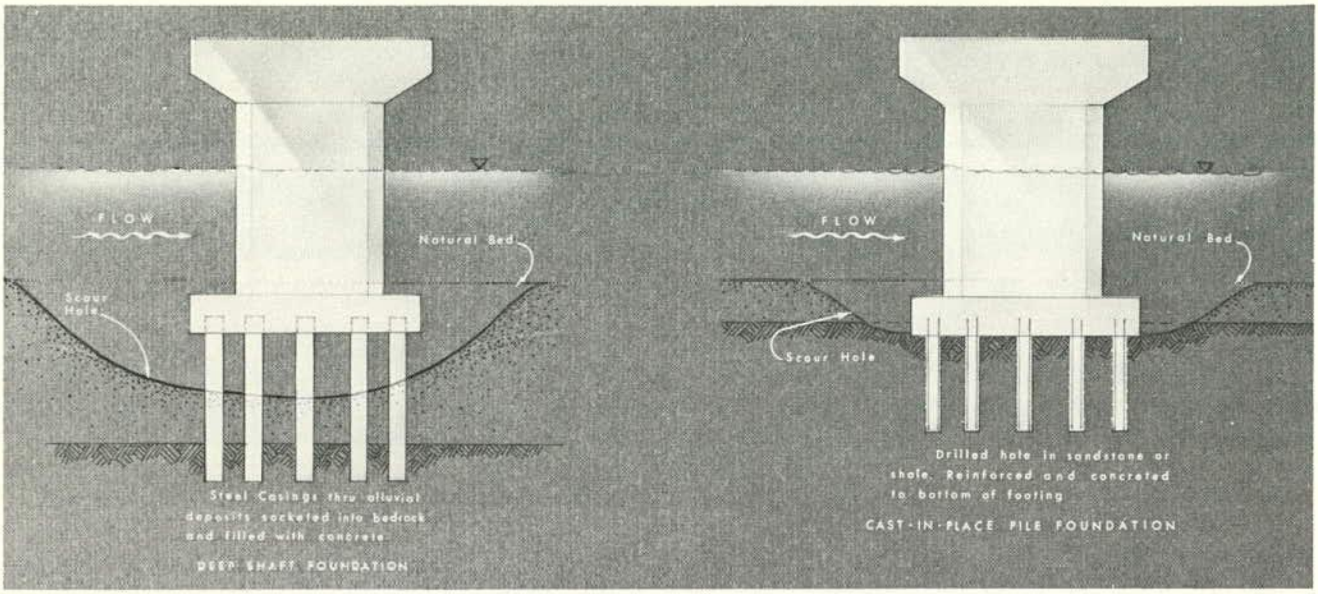


Figure 15. Drilled shaft foundations.

periodically, perhaps annually where known problems exist and bi-annually at more stable sites. Inspections are recommended during and after floods, particularly for new structures where performance history has not been developed. The pending AASHO *Manual for Maintenance Inspection of Bridges* provides general guidelines.

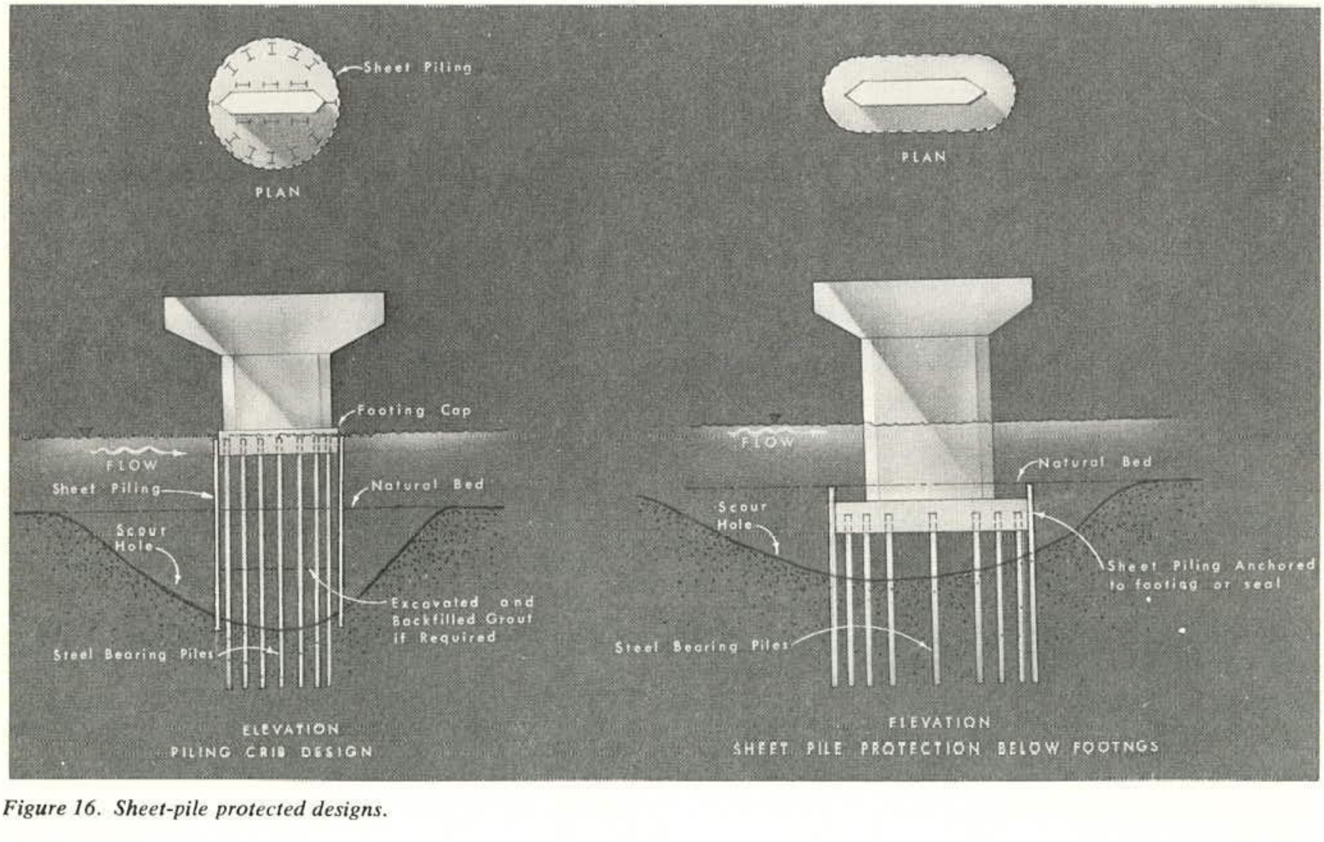


Figure 16. Sheet-pile protected designs.

Methods of Inspection

Probably the least expensive and most widely used method of inspection for scour consists of soundings with a weighted line. The principal shortcoming of this method is that soundings usually must be made after flooding has abated, and are not representative of the maximum scour that occurred during the flood. Soundings plotted as river bed contours afford a desirable means of monitoring progressive scour and shifting of the stream channel.

Limited experience to date indicates that soundings taken by sonar or echo-sounding devices vary from weighted-line soundings adjacent to massive piers, where heavy debris exists, or during flood conditions. However, the mobility of the sonar or similar type of sounding devices makes them advantageous for obtaining measurements at a number of locations and for various conditions. Their use is strongly recommended.

Where footings have been undermined, experienced divers offer the most reliable means for assessing scour and possible structural damage to bridge foundations. However, the use of divers during floods and in streams with high flow velocities is hazardous.

Where scour is expected to be a serious problem and measurements are required during flood, resistance measuring devices embedded in the bridge pier should be considered.

Routine Maintenance

Frequent visual inspections, often accompanied by depth soundings, will indicate the necessity of removing debris and ice from in front of piers, and lining minor scour holes with riprap or heavy stone.

CHAPTER FIVE

RESEARCH NEEDS AND PRIORITIES

CURRENT RESEARCH

A number of agencies are currently engaged in research into various aspects of the scour problem. Included are such factors as downstream protection, magnitude of scour during floods, ways of reducing scour, and investigation of modeling criteria. Table 4 lists a number of current research projects. It is readily acknowledged that this is not a comprehensive listing and that productive research is probably in initial or continuing stages in many universities and other research-oriented agencies. Omission of these agencies was not intended. It is hoped that they will make themselves and their research topics known, whether they be directly or indirectly related to scour around bridges.

NEED FOR RESEARCH

The problem of bridge pier scour has been studied off and on since at least 1894, when H. Engels (Germany) published the results of model experiments on piers of various shapes. It is also noteworthy that structural engineering textbooks at the turn of the century discussed the problem of scour at some length. They stopped short, however, of giving any rules for predicting scour.

After 80 years of research one might wonder why there are not more answers, why more research is needed. Possibly the reason is that there has been little sustained research; investigators have picked up the problem, repeated to a considerable degree what others had done (unknowingly or knowingly), and then dropped it without making any considerable contribution to the knowledge of the phenomenon. Most experiments have been run with clear water (no sediment supply), field measurements are almost nonexistent (or unavailable), and the few analyses made usually consist of curve fitting to a limited amount of model data.

Probably the most comprehensive study was made at the University of Iowa between 1948 and 1958. The difference between clear-water scour and scour by sediment-transporting flow was realized, the abutment as well as the pier was investigated, approximate analyses were offered, and measurements were made at a prototype site of simple geometry. Colorado State University has also studied the problem quite extensively and has thereby enlarged the geometry which has been considered. Various relationships for scour have been proposed by the University of Iowa and Colorado State University.

Other investigators have made less extensive studies, some of them of only bits and pieces of the general problem. Most of the relationships that have been proposed for predicting scour are listed in Appendix B, and the University of Iowa relationships are summarized in Appendix C.

RESEARCH PRIORITIES

The first priority in research on scour problems should be given to field measurements. No relationship for predicting scour can be used with confidence until proof has been shown that it does predict what happens with reasonable accuracy and reliability.

TABLE 4

SUMMARY OF KNOWN RESEARCH ACTIVITIES RELATED TO SCOUR AT BRIDGE WATERWAYS[a]

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO.[b]
Investigation of Scour at Bridges in Alaska	U. S. Geological Survey and Alaska Dept. of Highways	23 012949
Scale Effects in Model Tests of Rock-Protected Structures	University of Iowa	23 013154
Engineering Investigation Pertaining to Flood Protection of Bridges and Culverts	Colorado State University and Wyoming Highway Department	23 017088
River Bed Scour at Bridge Piers and Abutments and Channel Control	Canadian Good Roads Association	23 050007
Scour at Bridge Piers	Ministry of Works (New Zealand)	23 060802
Scouring at Bridge Piers	National University of Mexico	23 060905
Scour Occurring Around a Bridge Pier	Public Works Res. Inst., CM (Japan)	23 060986
Reduction of Scour Around Bridge Piers	South Dakota State University, Brookings	23 088442
River Bed Scour	Alberta Coop. Highway Research Program (Canada)	27 050197
Pier Scour at a Bridge	Rio Grande University, Hydr. Res. Inst. (Brazil)	63 060962

[a] As of July 1970. [b] Acquisition number assigned by the Highway Research Information Service of the Highway Research Board; HRIP = publication entitled *Highway Research in Progress* (current issue).

Because measurements are so difficult to make during a flood, an initial investigation should be made at bridges in large rivers during moderately high flows. Advantages of such an investigation would be a chance to repeat measurements, or to obtain additional measurements if necessary. The measurements that are needed at the very least are (1) the stream bed configuration in the approach channel and around the pier or abutment (i.e., the scour depth, the scour pattern, and the bed form); (2) the flow pattern, including the flow direction, the flow velocity, and the depth; (3) the bed material, both in the stream and in the scour hole; and (4) the bridge and channel geometry. It may well be that other factors should be considered and more detail will be needed; however, in the beginning a simple program is recommended involving measurements that can be made with existing techniques at various sites. This will, in effect, extend the scale of the laboratory model. Sites with simple geometry are needed because these will involve the least ambiguity when compared to laboratory data and to analyses. However, sites of complex geometry are also needed because only in this way can it be discovered whether a very approximate rendition of the flow pattern can achieve useful results.

Efforts should also be made to obtain measurements at various kinds of bridge sites during floods—despite the difficulty of making measurements during floods. At least as much detail would be desired in these measurements; but practically, one should be willing to settle for less. The first difficulty is that floods do not take place on demand. If permanent instrumentation is installed, the floods that occur may for years be very minor. On the other hand, if portable instrumentation is adopted, it may not be possible to catch the flood where and when it occurs. The second difficulty is the danger of making measurements during a flood; the high velocity and the drift make operations from a boat risky. However, these difficulties may be overcome by studying bridges below dams where a controlled release is feasible.

A third type of study that might be explored is hindcasting of past events. Floods have occurred on streams, or in areas, where some bridges have failed or been damaged and other bridges have been unimpaired. Estimates of the scour that should have occurred for that flood, and of the maximum scour that could occur without damage might correlate with the damage that actually occurred. If so, the confidence in estimates of scour should be improved considerably. If not, perhaps a second examination would indicate factors that need further consideration. The acquisition and centralization of data on the failure and nonfailure of bridges during floods would be a partial step.

The second priority in research should be given to the estimation of rare floods. Other highway hydraulics problems require knowledge of the magnitude of frequent floods, and such knowledge is one starting point for the estimation of the magnitude of rare floods. However, few streams have the length of record necessary for a good determination of a 50-year flood, and extrapolation to rarer floods is accompanied by less and less confidence. Research into the question of the maximum probable flood is needed, as this would place bounds on the rare floods.

The third priority in research should be given to the problem of estimation of the erodibility of cohesive soils and soft rock. Standard tests giving at least a relative erodibility index could be useful. It should be noted, however, that a small sample of foundation material may give misleading information because weak seams comprising a minor part of the underlying material may control the behavior of the mass. Past attempts to relate erodibility with the soil mechanics characteristics of cohesive sediments have not been very successful. Perhaps the examination of the soil fabric by such techniques as electron microscopy would be productive.

The fourth priority in research should be given to the laboratory and analytic study of the effect of geometry, etc., on the depth and extent of scour. This in time might become the first priority. There are some experiments that could be run, or rerun, now which might better define the effects of the various factors determining scour. Mostly, they would be refinements on what has already been done, and whether or not they are worth doing is debatable. There is little doubt, however, that as the results of field investigations begin to come in there would be need to go back to the laboratory—and to analysis.

Therefore, the prime recommendation is that available funds for research should be used for field investigations; first, the measurements that can be made now, and, second, the measurements that would be more satisfying. Then, what is known and what is not known would be placed in a clearer light and other research needs would be more apparent.

RESEARCH TOPICS

Specific research topics often mentioned include:

1. Methods of determining horizontal and vertical extent of scour.
2. Use of underwater television, radioactive materials, echo-sounding equipment, etc., to determine scour.
3. Methods of sampling material during scouring activity; use of weighted tubes, etc.
4. Further development of drilling and sampling techniques in detecting evidences of previous scour, and in providing information on scour potential of foundation materials.

Successful research on these four topics would improve field measurements—but should not delay a field measurement program using presently available equipment.

5. Basic research into runoff capabilities of small watersheds. (The current data collection programs on small watersheds should give this topic meaning in the near future.)
6. Effect of channel obstructions on total scour.
7. Use of deflectors and traps to reduce scour caused by debris accumulation at piers.
8. Effectiveness of local protection:
   (a) Willow (or lumber) mats.
   (b) Cofferdams.
   (c) Riprap.
   (d) Spur dikes.
   (e) Auto body "necklaces."

Topics 6, 7, and 8 represent normal questions confronting the designer. A quantitative comparison of different designs, however, demands a method of predicting scour—and field measurements are necessary to validate any method of prediction.

9. Basic research into mobile-bed hydraulics, particularly into the scale effect of bed material.
10. Criteria for determining length of spur dikes, and when to use them.

The scour phenomenon is a special case of the general problem of mobile-bed hydraulics or sediment transportation. The more that is known about the general problem, the more likely becomes a satisfactory solution of the special case. Hopefully, however, a reasonable, satisfactory solution to the scour problem can be achieved with the present state of knowledge—especially since the magnitude of the flood and the pattern of the flow cannot be known with precision and confidence.

APPENDIX A

SELECTED BIBLIOGRAPHY

1. AHMAD, M., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY9, Part I, pp. 144-151 (1960).
2. AHMAD, M., Discussion of "Scour at Bridge Crossings." *Trans. ASCE,* Vol. 127, Part I, pp. 198-206 (1962).
3. AHMAD, M., "Effect of Scale Distortion, Size of Model Bed Material and Time Scale on the Geometrical Similarity of Localized Scour." *Proc. Internat. Assn. for Hydr. Res.*, The Hague (1955).
4. AHMAD, M., "Experiments on Design and Behavior of Spur Dikes." *Proc. Internat. Assn. for Hydr. Res. Conv.*, Univ. of Minnesota (1953), pp. 145-159.
5. ANDERSON, A. G., "The Hydraulic Design of Bridges for River Crossings—A Case History." *Hwy. Res. Record No. 123* (1966) pp. 1-16.
6. ARUNACHALAM, K., "Scour Around Bridge Piers." *Jour. Indian Roads Congress,* Vol. 29, No. 2, pp. 189-210 (Aug. 1965); *Hwy. Res. Abst.*, Vol. 36, No. 4, pp. 1-2 (Apr. 1966).
7. BLENCH, T., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY5, pp. 193-194 (1960).
8. BLENCH, T., *Mobile Bed Fluviology.* Univ. of Alberta Press (1969).
9. BLENCH, T., *Regime Behaviour of Canals and Rivers.* Butterworths (London) (1957) 138 pp.
10. BRADLEY, J. N., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY8, pp. 69-70 (1960).
11. BRADLEY, J. N., "Hydraulics of Bridge Waterways." *Hydraulic Design Series No. 1,* Bur. Pub. Roads (Rev. 1970) 111 pp.
12. COLBY, B. R., "Scour and Fill in Sand-Bed Streams." *Prof. Paper 462-D,* U.S. Geological Survey (1964), pp. D1-D32.
13. CORRY, M. L., and SAGER, W., "Ultrasonic Instrument for Determining Local Scour at Bridge Piers." *Pub. Roads,* Vol. 35, No. 4, pp. 91-96, 108 (Oct. 1968).
14. CULBERTSON, D. M., *Scour and Fill in Alluvial Channels with Particular Reference to Bridge Sites.* U.S. Geological Survey (1967) 58 pp.
15. ERICKSON, L. L., "Some Measurements of Velocities and Scour at a Mississippi River Bridge Pier." *Proc. HRB,* Vol. 26 (1946) pp. 124-128.
16. GARDE, R. Y., SUBRAMANYA, K., and NAMBUDRIPAD, K. D., "Study of Scour Around Spur Dikes." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 87, No. HY6, pp. 23-37 (1961).
17. HERBICH, H. P., and BRENNAN, L. M., "Prediction of Scour at Bridges." *Rept. No. RR 115,* Ontario Dept. of Highways (Apr. 1967) 135 pp.; *Hwy. Res. Abst.*, Vol. 37, No. 11, p. 2 (Nov. 1967).
18. HICKENLOOPER, I. J., GUILLOU, J. C., and CHOW, V. T., "Hydraulic Studies of a Highway Bridge." Dept. of Civil Engineering, Univ. of Illinois (1957) 76 pp.
19. HUBBARD, P. G., "Field Measurement of Bridge-Pier Scour." *Proc. HRB,* Vol. 34 (1955) pp. 184-188.
20. JOGLEKAR, D. V., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY9, Part I, pp. 129-132 (1960).
21. KARAKI, S. S., "Hydraulic Model Study of Spur Dikes for Highway Bridge Openings." *Report CER 59 SSK 36,* Colorado State Univ., Fort Collins (1959) 47 pp.
22. KARAKI, S. S., "Laboratory Study of Spur Dikes for Highway Bridge Protection." *HRB Bull. 286* (1961) pp. 1-12.
23. KARAKI, S. S., and HAYNIE, R. M., "Mechanics of Local Scour: Part II: Bibliography." *Rep. No. CER 63 SSK 46,* Colorado State University (1963) 51 pp.
24. LANE, E. W., and BORLAND, W. M., "River Bed Scour During Floods." *Trans. ASCE,* Vol. 119, pp. 1069-1089 (1954).
25. LAURSEN, E. M., "An Analysis of Relief Bridge Scour." *Proc. ASCE,* Vol. 89, No. HY3, pp. 93-118 (1963).
26. LAURSEN, E. M., "Bridge Design Considering Scour and Risk." *Proc. ASCE, Transport. Eng. Jour.*, Vol. 96, No. TE2, pp. 149-164 (May 1970).
27. LAURSEN, E. M., "Model-Prototype Comparison of Bridge-Pier Scour." *Proc. HRB,* Vol. 34 (1955) pp. 188-193.
28. LAURSEN, E. M., "Observations on the Nature of Scour." *Proc. 5th Hydraulics Conf.*, State Univ. of Iowa (1953).
29. LAURSEN, E. M., "Progress Report on Model Studies of Scour Around Bridge Piers and Abutments." *HRB Res. Rep. 13-B* (1951) pp. 1-11.
30. LAURSEN, E. M., "Scour at Bridge Crossings." *Trans. ASCE,* Vol. 127, Part 1, Paper 3294, pp. 166-209 (1962).
31. LAURSEN, E. M., "Scour at Bridge Crossings." *Iowa HRB Bull. No. 8* (Aug. 1958) 53 pp.
32. LAURSEN, E. M., "Some Aspects of the Problem of Scour at Bridge Crossings." Federal Inter-Agency Sedimentation Conf., Jackson, Miss., pp. 304-309 (1963).
33. LAURSEN, E. M., "The Total Sediment Load of a Stream." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 84, No. HY1, Paper No. 1530 (1958).
34. LAURSEN, E. M., and TOCH, A., "A Generalized Model Study of Scour Around Bridge Piers and Abutments." *Proc. Internat. Assn. for Hydr. Res.*, Univ. of Minnesota (1953) pp. 123-131.
35. LAURSEN, E. M., and TOCH, A., "Model Studies of Scour Around Bridge Piers and Abutments—Second

Progress Report." *Proc. HRB*, Vol. 31 (1952) pp. 82-87.
36. LAURSEN, E. M., and TOCH, A., "Scour Around Bridge Piers and Abutments." *Iowa HRB Bull. No. 4* (May 1956) 60 pp.
37. LEVEEN, L. S., "Investigation of Scour at Selected Bridge Crossings in Alaska." U.S. Geological Survey, Water Resources Div., Progress Reports, 30 pp. (Nov. 1966) and 28 pp. (Apr. 1967).
38. LIU, H. K., and SKINNER, M. M., "Laboratory Observations of Scour at Bridge Abutments." *HRB Bull. 242* (1960) pp. 69-77.
39. MOULTON, L. K., BELCHER, C., and BUTLER, B. E., "Report on Investigation of Scour at Bridges Caused by Floods of 1955." *Hwy. Res. Abst.*, Vol. 27, No. 8, pp. 14-31 (Sept. 1957).
40. NEILL, C. R., Discussion of "Scour Around Spur Dikes." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 88, No. HY2, pp. 191-192 (1962).
41. NEILL, C. R., "Introduction to the Problem of Scour at Bridges." Paper presented to the Subcommittee on Bridge Scour, Committee on Bridges and Structures, Canadian Good Roads Assn., Winnipeg, Manitoba (1963).
42. NEILL, C. R., "Measurements of Bridge Scour and Bed Changes in a Flooding Sand-Bed River." *Proc. Inst. Civil Eng.*, Paper 6775, pp. 415-436, (Feb. 1965); *Hwy. Res. Abst.*, Vol. 35, No. 6, p. 10 (June 1965).
43. NEILL, C. R., "River-Bed Scour: A Review for Bridge Engineers." *Tech. Pub. No. 23*, Canadian Good Roads Assn., (Dec. 1964) 37 pp.; *Hwy. Res. Abst.*, Vol. 35, No. 5, p. 9 (May 1965).
44. POSEY, C. J., "Why Bridges Fail in Floods." *Civil Eng.*, Vol. 19, No. 2, p. 94 (Feb. 1949).
45. POSEY, C. J., APPEL, D. W., and CHAMNESS, E., JR., "Investigation of Flexible Mats to Reduce Scour Around Bridge Piers." *HRB Res. Rep. 13-B* (1951) pp. 12-22.
46. SANDEN, E. J., "Scour at Bridge Piers and Erosion of River Banks." *Proc. 13th Ann. Conf.*, Western Assn. of Canadian Highway Officials (1960).
47. SANDEN, E. J., and NEILL, C. R., "Measuring Scour Around Bridge Foundations in Floods." *Pub. Works in Canada*, Vol. 11, No. 7, pp. 14-17 (1963).
48. SCHNEIBLE, D. E., "An Investigation of the Effect of Bridge Pier Shape on the Relative Depth of Scour." M. S. Thesis, Univ. of Iowa (1951) 92 pp.
49. "Scour Around Bridges." *HRB Res. Rep. 13-B* (1951) 22 pp.
50. SEARCY, J. K., "Use of Riprap for Bank Protection." *Hydr. Eng. Circ. No. 11*, Bur. of Public Roads (June 1967) 43 pp.
51. SHEN, H. W., SCHNEIDER, V. R., and KARAKI, S. S., "Local Scour Around Bridge Piers." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 95, No. HY6, pp. 1919-1940 (Nov. 1969).
52. SHEN, H. W., SCHNEIDER, V. R., and KARAKI, S. S., "Mechanics of Local Scour." CER66HWS22, Eng. Res. Center, Colorado State Univ. (June 1966) 57 pp.
53. "Short Piles at Big Sioux." *Eng. News-Rec.*, Vol. 168, No. 18, p. 17 (May 3, 1962).
54. STABILINI, L., "Scour at Bridge Piers: Cause and Effect." *Civil Eng.*, Vol. 33, No. 5, pp. 46-47 (May 1963).
55. STRAUB, L. G., "Dredge Fill Closure of Missouri River at Fort Randall." *Proc. Internat. Assn. for Hydr. Res.*, Univ. of Minnesota (1953).
56. THOMAS, A. R., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY9, Part I, pp. 142-143 (1960).
57. TISON, L. J., Discussion of "Scour at Bridge Crossings." *Proc. ASCE, Jour. Hydr. Div.*, Vol. 86, No. HY9, Part I, pp. 134-137 (1960).
58. TISON, L. J., "Studies of Critical Tractive Force for the Entrainment of Bed Materials." *Proc. Internat. Assn. for Hydr. Res.*, Univ. of Minnesota (1953).

APPENDIX B

PRINCIPAL RESEARCHERS—FORMULAS AND CHARTS

AHMAD

Ahmad's (1962) formula (*43*),

$$D_s = Kq^{2/3}$$

in which

D_s = depth of scour from water surface;
q = average discharge intensity, equal to design flood discharge divided by clear waterway width; and
K = a multiplying factor selected according to the general situation of the bridge and other conditions. Varies from 1.3 to 2.3.

was derived for bridges crossing alluvial rivers in deep sand fills in Pakistan, and is based on field experience and model studies. The form of the equation can be obtained from the solution for the long contraction, $y_2/y_1 = (B_1/B_2)^{2/3}$ by assuming $D_s = y_2$. The relationship that results is $D_s/(Q/B_2)^{2/3} = K = y_1/(Q/B_1)^{2/3}$, which could be interpreted as requiring that the Froude number be the same in the contraction as in the upstream uncontracted flow. However, the depth of scour, D_s, could be assumed as not equal, but proportional to y_2; the coefficient of proportionality being dependent on the geometry of the situation. Inasmuch as the long contraction solution can be obtained from continuity as applied to the sediment transport rate and the discharge, what appears to be a Froude requirement might be a sediment transport, or shear, requirement.

BLENCH

Blench's equation (*8, 43*),

$$D_s/y_r = 1.8\ (b/y_r)^{1/4}$$

in which

D_s = depth of scour from water surface;

$y_r = \sqrt[3]{q^2/F_b}$ (regime depth);

$F_b = 1.9\sqrt{_{mm}}$;

q = average discharge intensity;

d_{mm} = mean diameter of bed sand, in mm; and

b = width of pier.

can be obtained from the Inglis-Poona equation following, if the exponent 0.78 is changed to 0.75. The limitations of the Poona equation are therefore inherent, and contradictory because the conditions of the Poona tests were those of clear-water scour and regime theory implies a low to moderate rate of sediment movement.

BREUSERS

Breusers' (1964-5) equation (*51*),

$$d_{se}^* = 1.4\ b$$

in which

d_{se}^* = maximum equilibrium scour measured from mean bed elevation; and

b = width of pier projected on a plane normal to the undisturbed flow.

was based on model studies of drilling spuds in waves and currents. The lack of velocity and sediment size factors might indicate either that it is applicable to the sediment-transport case, or that ambient conditions are just at the critical for movement of the bed material.

CHITALE

Chitale's (1941) formula (*30*),

$$y = 6.65\mathbf{F} - 0.51 - 5.49\mathbf{F}^2$$

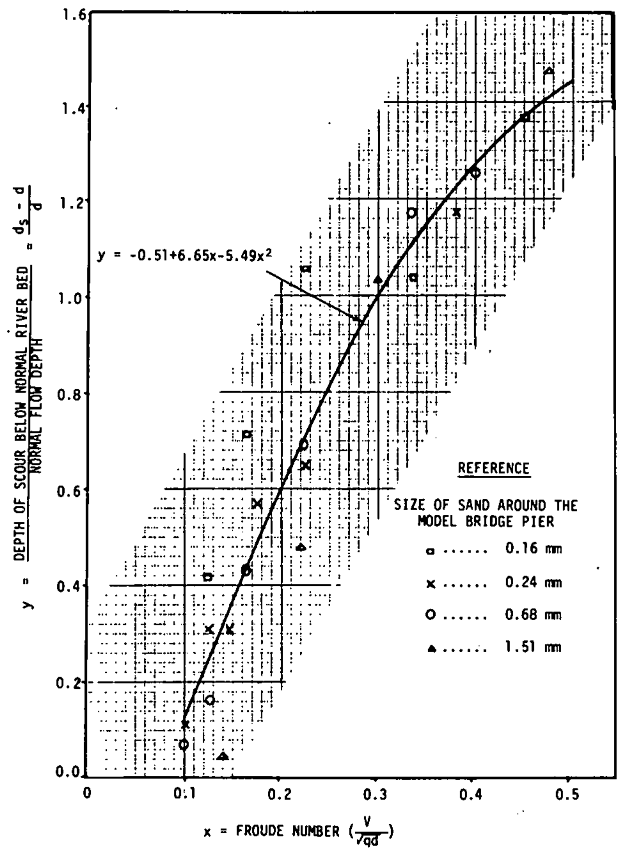


Figure B-1. Chitale's equation.

in which $\mathbf{F} = V/\sqrt{g\,d}$, is based on the results of an extension of the original Poona model tests of the Hardinge (India) bridge. Most of the tests were for the case of clear-water scour; but for some where there was coarse sand laid around the pier, the finer sand from upstream in the flume moved down to the scoured area.

INGLIS-POONA

The Inglis-Poona (1938) equation (*30*),

$$D_s/b = 1.70\ (q^{2/3}/b)^{0.78}$$

in which

D_s = depth of scour from water surface;

q = average discharge intensity; and

b = width of pier.

is based on a series of model tests of the Hardinge (India) bridge pier run without general movement of the bed. However, in application no distinction has been made between clear-water scour and scour by sediment-transporting flow. The use of q, the discharge per unit width in the contraction, would seem to imply greater scour at the piers if more piers were placed in the cross-section. This implied general contraction effect might be actually the velocity effect for clear-water scour.

INGLIS-LACEY

The Inglis-Lacey (1949) relationship (*30*),

$$D_s = 0.946\ (Q/f)^{1/3}$$

in which

D_s = depth of scour from water surface;

Q = discharge, in cfs;

f = Lacey silt factor = $1.76\sqrt{d_{mm}}$;

d_{mm} = mean diameter of bed sand, in mm.

is a statement that the depth of scour measured from the water surface is twice the Lacey regime depth. An alternative equation for the Lacey regime depth, also assuming the hydraulic radius is equal to the depth, is $V = 1.1512\sqrt{f\,y_r}$. The principal restriction of this relationship is that of the Lacey, or regime, channel. However, it also ignores the pier size, shape, and alignment.

LARRAS

Larras' equation (*51*),

$$d_{sc}{}^* = 1.42\ K\ b^{0.75}$$

in which

$d_{sc}{}^*$ = maximum equilibrium scour measured from mean bed elevation;

K = coefficient dependent on pier shape 1.0 for cylindrical piers, 1.4 for rectangular piers aligned with the flow; and

b = width of pier projected on a plane normal to the undisturbed flow.

was derived from measurements of scour data taken from various French rivers after the passage of the flood. It was also influenced by the model studies of Chabert and Engeldinger.

LAURSEN

There are several Laursen (Iowa, 1956) relationships (*36*). The first, presented by Laursen and Toch, was a conservative curve drawn by eye to model study data for the sediment-transporting case. Multiplying factors for the shape or angle of attack were also presented. The Laursen (II) relationship,

$$b/y_o = 5.5\ d_s/y_o\ (d_s/r\,y_o + 1)^{1.7} - 1$$

was based on an analysis adapting the solution of the long contraction, with a balance of sediment-transport capacity in the normal and contracted sections, to the pier (or abutment). The Laursen (III) relationship,

$$b/y_o = 5.5\ d_s/y_o\ [(d_s/r\,y_o + 1)^{7/6}/(\tau_o'/\tau_c)^{1/2} - 1]$$

where $\tau_o'/\tau_c = V^2/120\ D^{2/3}\ y_o{}^{1/3}$, was similarly adapted from an analysis of long contraction in which the contraction scoured to give a boundary shear equal to the critical tractive force for the bed material and the shear in the approach was less than this value. A summary of the Laursen relationships is presented in Appendix C.

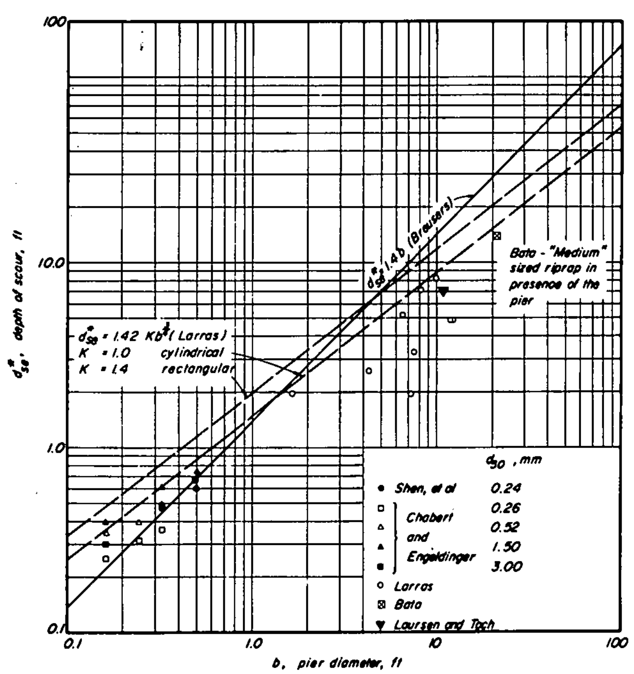


Figure B-2. Maximum scour depth (Larras) as a function of pier width, where the pier is assumed to be aligned with the flow.

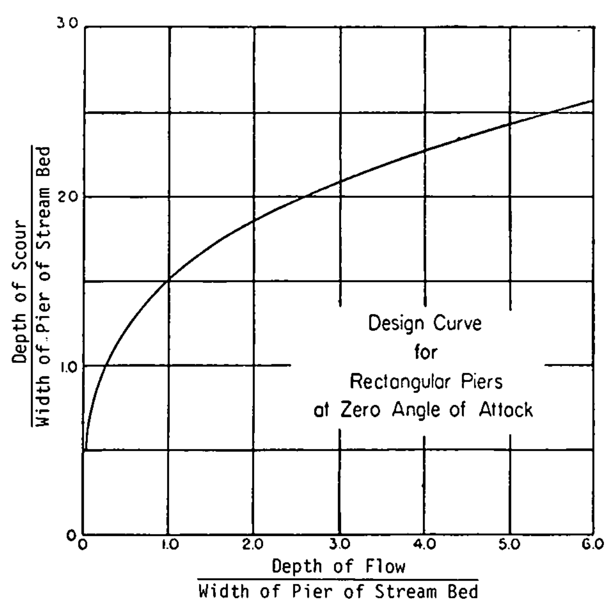


Figure B-3. Laursen's basic design curve for depth of scour.

NEILL

Neill's (1964) equation (*8*),

$$d_s/b = 1.5\ (y/b)^{0.3}$$

or

$$d_s/y = 1.5\ (b/y)^{0.7}$$

is based on model study data and is supposedly the maximum scour that can occur at any velocity. By implication, therefore, it is for the condition of impending motion on the approach stream bed, which most evidence indicates is somewhat larger than for the sediment-transporting case. For round-nosed piers, the coefficient should be changed to 1.2; for oblique piers the width, b, is taken as the projected width and the coefficient 1.5 is used for all non-aligned shapes.

SHEN

The Shen (1966, 1969) equations (*51, 52*),

$$\text{(I)} \quad d_{se} = 0.00073\ R^{0.619}$$

in which

d_{se} = equilibrium depth of scour measured from mean bed elevation;

R = pier Reynolds number = $V\ b/\nu$;

V = mean velocity of the undisturbed flow;

b = width of pier projected on a plane normal to the undisturbed flow; and

ν = kinematic viscosity.

$$\text{(II)} \quad (1)\ \frac{d_{se}}{b} = 11.0\mathbf{F}^2$$

$$(2)\ \frac{d_{se}}{b} = 3.4\mathbf{F}^{0.67}$$

in which $\mathbf{F}$ = pier Froude number = $V/\sqrt{g\,b}$, are based on model studies conducted at Colorado State University and other measurements, and are for the limiting case of clear-water scour where, presumably, conditions in the approach flow are impending movement of the bed material. In each form there is a velocity effect but not a sediment-size effect. The limiting depth of scour predicted must be interpreted as the depth of scour that would occur for a bed material which would be at the point of incipient movement for the given flow conditions. Otherwise, the flow conditions must be those that would result in incipient movement of the given bed material.

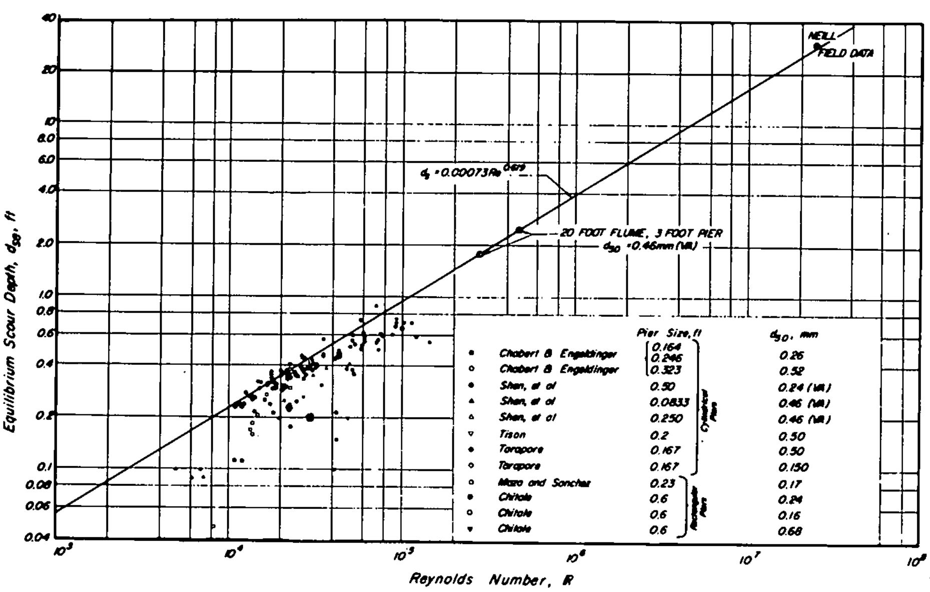


Figure B-4. Shen's comparison of scour data.

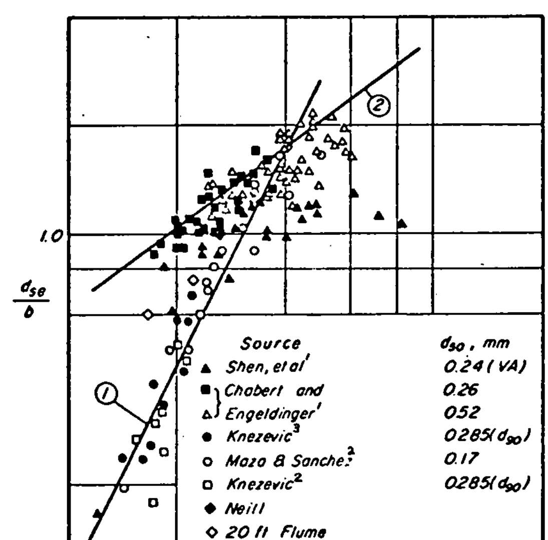


Figure B-5. Shen's equilibrium scour depth-pier width ratios as a function of the pier Froude number.

APPENDIX C

BRIDGE DESIGN CONSIDERING SCOUR AND RISK *

THE ACCEPTABLE RISK OF BRIDGE FAILURE DUE TO SCOUR

Bridges should be designed to withstand the scour at pier and abutment foundations that could occur during the maximum probable flood. To accomplish this the designer must first estimate the magnitude of the maximum probable flood, then predict the flow pattern at the bridge for that flow, and finally predict the scour that will occur at the piers and abutments.

The inadequacy of the 50-year rule is illustrated by Figures C-1, C-2, and C-3, in which a simple risk analysis is graphically portrayed (*26*). In Figure C-1, the sum of the cost of the bridge times the probability of loss plus the added cost of foundations adequate for rarer and rarer floods is still dropping for a design flood of the 10,000-year recurrence interval. The conditions for this simple case were: a bridge 30 ft wide and 1,333 ft long; having a life of 25 years; and costing $10 per square foot, including basic piers and abutments; ten round-nosed piers 5 ft wide with 25 piles per pier costing $4 per foot per pile; and a river with high banks (no overbank flow) with a flood magnitude-frequency relation that plots as a straight line on log-normal paper ($Q_{10} = 66,666$ cfs, $Q_{50} = 133,333$ cfs). For the second case (Fig. C-2) the depth of scour was increased by skewing the 30-ft-long piers 30° to the flow, and decreasing the cost of the bridge arbitrarily to $2.50 per square foot, to $0.625 per square foot, and to $0.25 per square foot. Only for this last extremely low-cost bridge did the 50-year rule apply. Slightly different conditions were assumed for the abutment case (Fig. C-3).

* By E. M. Laursen, Professor of Civil Engineering, University of Arizona.

The bridge was taken as 30 ft wide and 250 ft long; with a life of 25 years; costing $10 per square foot; each abutment was considered to be placed on 25 piles costing $4 per foot per pile; and the river was assumed to be bankfull at the 2.33-year flood and have a flood magnitude-frequency relation that plotted as two straight lines on log-normal paper ($Q_{2.33} = 8,000$ cfs, $Q_{10} = 16,000$ cfs, $Q_{50} = 24,000$ cfs). The indicated design-frequency flood would be about a 2,000-year recurrence interval.

Whether there is such a thing as a 1,000-year or a 10,000-year flood, even in the abstract, is debatable. Practically, these rare floods are the same as the maximum probable flood, the error of estimate being such that a given magnitude of flood is as likely to be one as another. Fortunately, the shape of the curve is flat enough at the minimum so one solution is about as good as another, and the design flood is so large in magnitude and so rare in occurrence that a failure can be excused.

By designing for the maximum probable flood, the risk of failure is reduced to that entailed by the error in estimating the flood, the error in assessing the flow pattern at the bridge, and the error in predicting the scour. This risk becomes almost nil as the errors in estimating, assessing, and predicting become smaller (or as the estimating, assessing, and predicting are more conservative). But the risk must be almost nil because the cost of failure is many times the cost of insuring against failure.

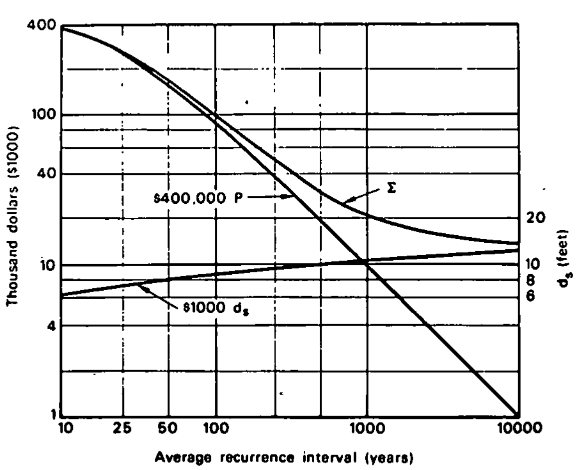


Figure C-1. Risk analysis considering bridge pier scour.

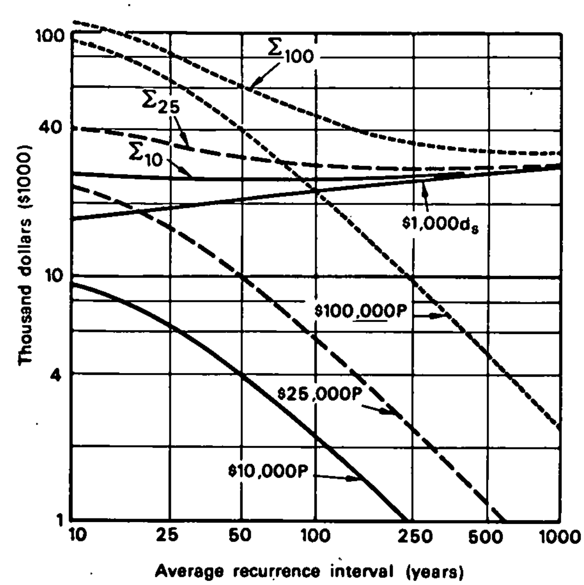


Figure C-2. Risk analysis considering relative bridge and foundation costs.

THE PHENOMENON OF SCOUR

Active scour will occur where the capacity of the flow to remove the boundary material is greater than the rate at which material is being supplied. When the area under consideration is a long reach of river, the term degradation is often used. Degradation is usually slow, because it involves a large area and tends to be continuous. It may be occurring naturally, with the stream as the geological agent of erosion, or it may be man-caused due to stream straightening, the result of augmentation of the stream flow, or the reduction of sediment supplied to a reach (as by a dam). The stream bed can be lowered 10 ft or more due to degradation; therefore, the likelihood of this type of action should be assessed in the hydraulic design of any bridge. Conversely, the vulnerability of existing bridges should be checked when river control works are planned that would result in degradation.

The opposite type of action, aggradation, in which there is deposition in the river channel, should also be assessed, because it too may create problems. The obvious problem is the raising of the water surface because of the rise in the stream bed in the long reach; this could cause the hangup of drift on the lower members of the bridge, which could restrict the waterway area under the bridge, which could increase the capacity of the flow locally to transport sediment, which could result in local scour greater than the general aggradation. Deposition in the river channel can also result in a greater percentage of the flood flow on the floodplain, which could conceivably result in added local scour at the abutments greater than the aggradation.

A long reach of river, especially one in flood, can be considered as a series of contractions and expansions that are, again, either man-made or natural because of topography and vegetation. During the rising flood, the contractions will scour and the expansions will fill; during the falling stages, the contractions will fill and the expansions will scour (*24*). Thus, the stream bed fluctuates up and down with each flood. With a complex geometry, and a residue of scour holes and deposition bars, the stream bed configuration can be extremely erratic and changeable.

The highway approach embankment on the floodplain will usually result in a large contraction and general, but not necessarily uniform, scour at the bridge site. To the extent that the flow on the floodplain moves into the channel before the immediate vicinity of the bridge, the general scour will tend to be uniform over the bridge site section. To the extent that the floodplain flow is concentrated at the abutment at the end of the embankment, the scour will tend to be local scour at the abutment.

Another possible cause for lowering the stream bed is a shifting of the channel. Meanders grow and progress downstream by scouring the outside bank and bed, filling the inside bank and bed. Bars grow and deep-water channels shift erratically in a braided channel. Such action can result first in a local lowering of the stream bed, and, second, in a change of flow pattern and, consequently, a change in the local scour at a pier or abutment.

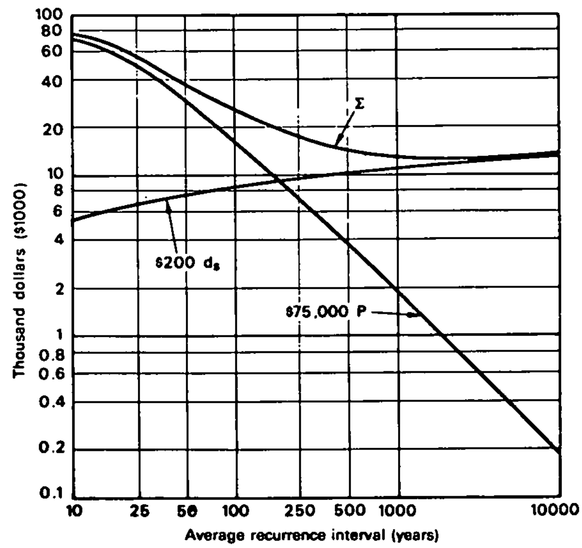


Figure C-3. Risk analysis considering abutment scour.

The local scour hole around a bridge pier or abutment is a direct consequence of the pier or abutment (and embankment) being an obstruction to the flow. The classic pattern is for the obstructed flow to dive down and pass by the obstruction as a spiral roller in the scour hole (Fig. C-4). The upstream part of the scour hole is a truncated cone with

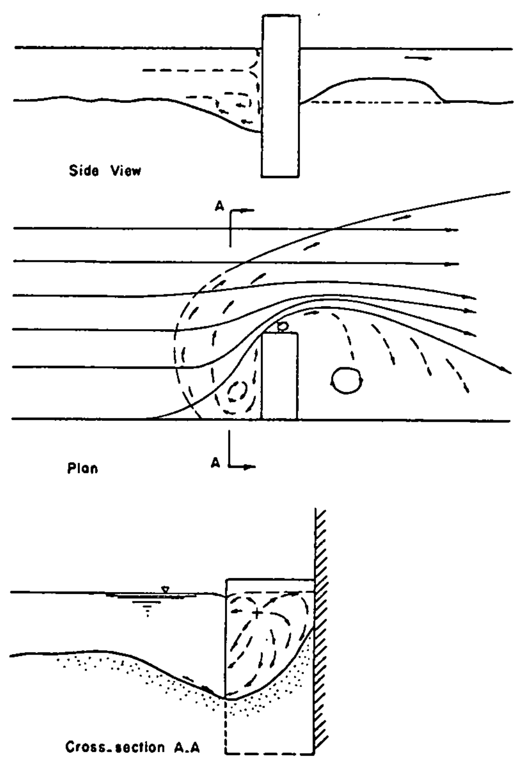


Figure C-4. Flow patterns in the vicinity of the scour hole.

the cone angle approximately the angle of repose of the sediment; downstream the side slopes flatten where the tail (or tails) of the spiral roller emerge and mix with the main flow. In the wake behind the pier or abutment, a dune or bar is formed.

In the absence of evidence to the contrary, scour of these different categories must be treated as additive. Judgment is necessary, however, as to the flow patterns that are likely to obtain. If degradation occurs, it can change the depth of approach flow to a pier and the percentage of flow circling the abutment. If much of the floodplain flow returns to the channel because of a natural contraction, little is left to cause local scour at the abutment.

ANALYSIS OF THE LONG CONTRACTION

The simplest case of scour, and the best to analyze, is the long contraction. The limit of scour in the contraction is the condition that results in continuity of flow and a balance of sediment supply and sediment-transport capacity. If the sediment supply is zero, the maximum stress on the boundary is the critical tractive force of the boundary material. The flow is assumed to be subcritical, the transition from wide to narrow section is ignored, and more or less acceptable expressions can be chosen to describe the flow and the capacity, or competence, for sediment transport.

Figure C-5 is a definition sketch of the long contraction of a river in flood. Neglecting the difference in velocity head and the loss in the transition, using the Manning formula to describe the flow and the following expression for the sediment transport, a solution can be obtained (*31*).

$$\bar{c} = \left(\frac{D}{y}\right)^{7/6} \left[\left(\frac{V^2}{120\, y^{1/3} D^{2/3}}\right) - 1\right] K \left(\frac{\sqrt{g y S}}{w}\right)^{a} \quad \text{(C-1)}$$

in which

$\bar{c}$ = sediment concentration (bed load plus suspended load) of the bed material that is scoured, in percent by weight;

D = diameter of the bed material, in feet;

y = depth of flow, in feet;

V = velocity of flow, in feet per second;

g = acceleration of gravity, in feet per second per second;

S = slope, in feet per foot; and

w = fall velocity of the sediment, in feet per second.

The exponent, a, and the coefficient, K, are dependent on the shear velocity-fall velocity ratio; K drops out of the analysis, and a varies approximately as follows:

$\frac{\sqrt{g y S}}{w}$	a
$<1/2$	$1/4$
1	1
>2	$9/4$

Neglecting the −1 factor in the term in brackets, certainly permissible for a river in flood, the depth ratio becomes

$$\frac{y_2}{y_1} = \frac{d_s}{y_1} + 1 = \left(\frac{Q_t}{Q_c}\right)^{6/7} \left(\frac{B_1}{B_2}\right)^{\frac{6(2+a)}{7(3+a)}} \left(\frac{n_2}{n_1}\right)^{\frac{6(a)}{7(3+a)}} \quad \text{(C-2)}$$

in which the symbols are as defined in Figure C-5.

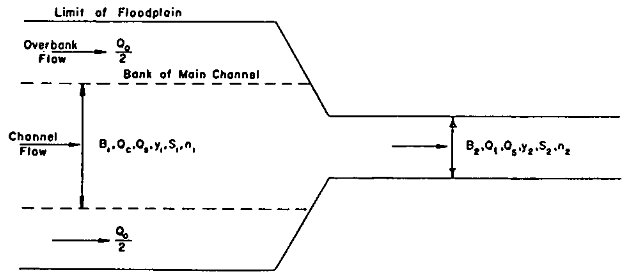


Figure C-5. Definition sketch of a long contraction.

The Manning n-ratio should generally be close to unity and its exponent is at the most 0.37, so the last term in Eq. C-2 usually can be neglected. The first term expresses the effect of a constriction of the overbank forcing the "clear" water on the floodplain into the channel; the second term expresses the effect of the channel flow being contracted. If both conditions are present, the total effect is multiplicative, not simply additive. The two separate effects, not the combined effect, are shown in Figure C-6.

The case of no supply can be solved in a similar fashion (*25*), and is useful when adapted to the case of the relief bridge on the floodplain and to the riprap question. Assuming that the approach boundary shear associated with the sediment particles can be obtained from the Manning formula and Strickler's evaluation of n, that the boundary shear in the channel contraction is the critical tractive force, equal to $4D$, the following expression can be obtained:

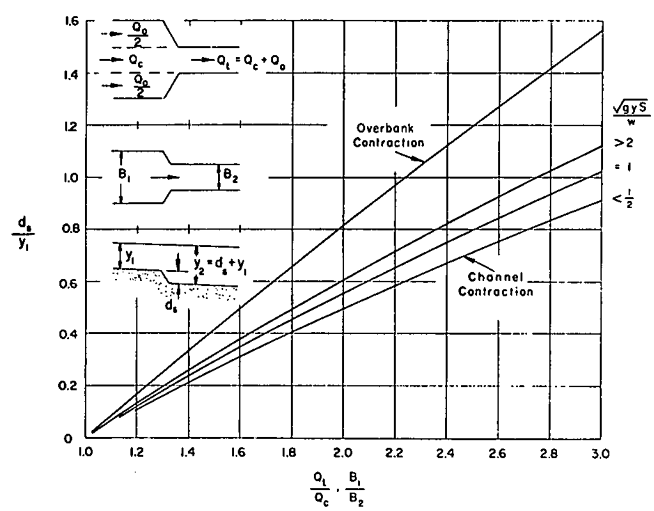


Figure C-6. Depth of scour in a long contraction.

$$\frac{y_2}{y_1} = \frac{d_s}{y_1} + 1 = \left(\frac{\tau_0'}{\tau_c}\right)^{3/7} \left(\frac{B_1}{B_2}\right)^{6/7} \qquad \text{(C-3)}$$

in which

$$\frac{\tau_0'}{\tau_c} = \frac{V_1^2}{120\, y_1^{1/3} D^{2/3}} \qquad \text{(C-4)}$$

This family of curves is shown in Figure C-7, together with the bed-load sediment-transporting case ($a = 1/4$).

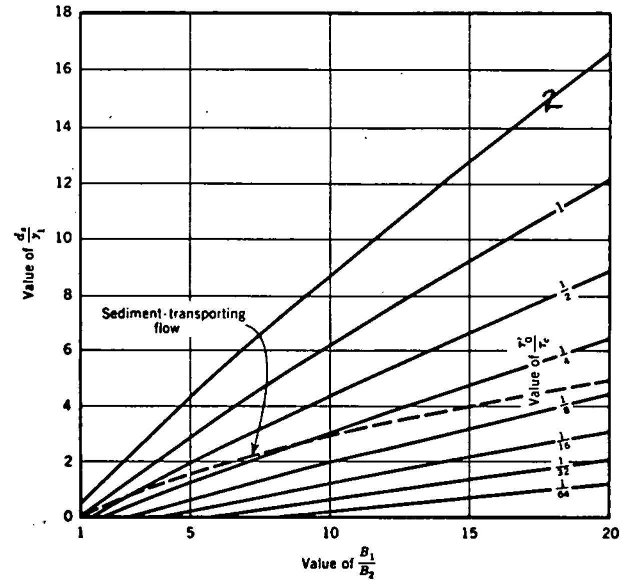


Figure C-7. Effect of shear ratio and width ratio on scour in a long contraction.

ANALYSIS OF PIER AND ABUTMENT SCOUR

Several observations of the flow pattern around piers and abutments allow adaptation of the long contraction case to the pier and abutment cases. For the simple geometries of a vertical-wall abutment (and embankment) or a blunt-nosed pier aligned with the flow, the upstream part of the scour hole is a truncated cone with side slopes at the angle of repose so that the hole extends laterally about 2.75 d_s in ordinary sands. The flow and the sediment load beyond (laterally) the scour hole are not observably affected by the pier (or abutment) or the scour hole. There could be a thin wall along the streamline tangent to the scour hole. The flow approaching the pier (or abutment) dives into the scour hole at the obstruction and forms a spiral roller in the scour hole. The flow approaching the scour hole, but not the obstruction (pier or abutment), slips by virtually unaffected, but the sediment being transported falls into the scour hole and slips down the angle of repose.

The adaptation of the long contraction solution to the abutment is shown in Figure C-8, in which an imaginary wall tangent to the scour hole and another parallel wall enclosing the wake behind the embankment form a fictitious long contraction. The depth of scour at the abutment is assumed to be a multiple of the depth of scour in the fictitious long contraction. The adaptation of the overbank constriction solution for the long contraction becomes

$$\frac{Q_o\, w}{Q_w\, y_0} = 2.75 \frac{d_s}{y_0}\left(\frac{1}{r}\frac{d_s}{y_0} + 1\right)^{7/6} - 1 \qquad \text{(C-5)}$$

in which

- Q_o = the flow on the adjacent floodplain being intercepted, in cfs;
- Q_w = the flow over the width, w, which by trial and error = 2.75 d_s;
- y_0 = the depth of flow approaching the scour hole, in feet; and
- r = the ratio of the depth of scour at the abutment to the depth of scour in the fictitious long contraction.

This relationship is shown in Figure C-9 with an r-value of 4.1.

The case of the channel contraction can similarly be adapted to the case of the abutment at the end of an embankment that encroaches into the channel. If the effective length of the embankment is λ, the uncontracted width, B_1, becomes $\lambda + 2.75\ d_s$ and the contracted width, B_2, is 2.75 d_s. For the bed load case ($\sqrt{g\, y\, S}/w < 1/2$) the relationship becomes

$$\frac{\lambda}{y_0} = 2.75 \frac{d_s}{y_0}\left(\frac{1}{r}\frac{d_s}{y_0} + 1\right)^{1.7} - 1 \qquad \text{(C-6)}$$

in which the effective length is evaluated so that the obstructed flow, Q_λ, if it flowed at a depth y_0, would have the same velocity as the flow approaching the scour hole, or

$$Q_\lambda / (\lambda\, y_0) = Q_w / (w\, y_0) \qquad \text{(C-7)}$$

in which, by trial and error, $w = 2.75\ d_s$. This relationship is shown in Figure C-10 with an r-value of 11.5.

Eq. C-6 can be further modified for the case of the rectangular pier aligned with the flow by substituting the

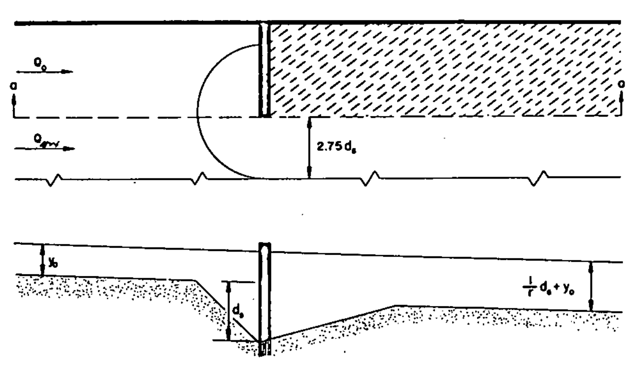


Figure C-8. Definition sketch of an overbank bridge constriction.

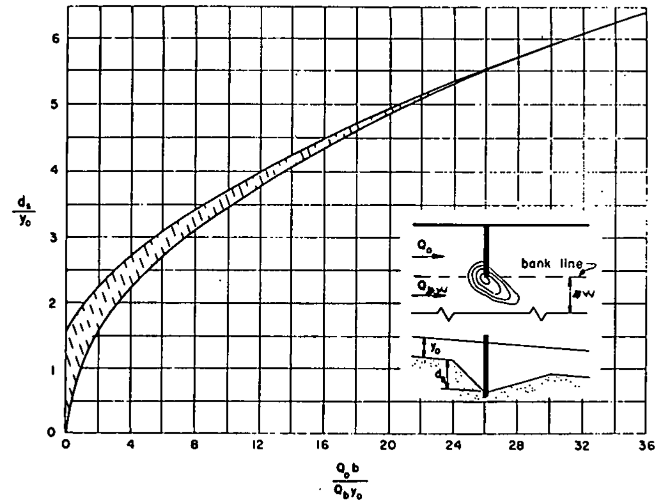


Figure C-9. Basic design curve for an overbank bridge constriction.

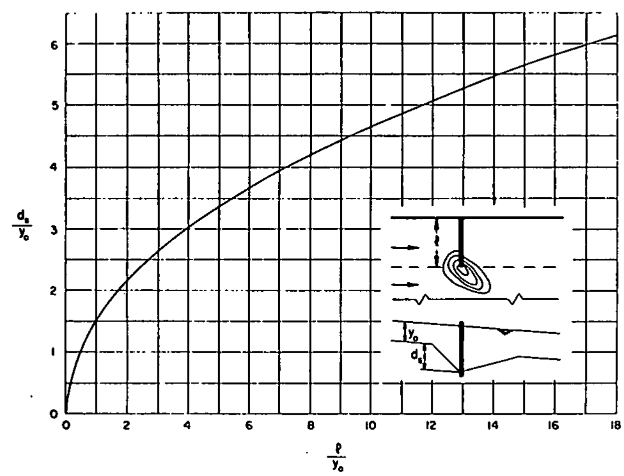


Figure C-10. Basic design curve for encroaching abutments.

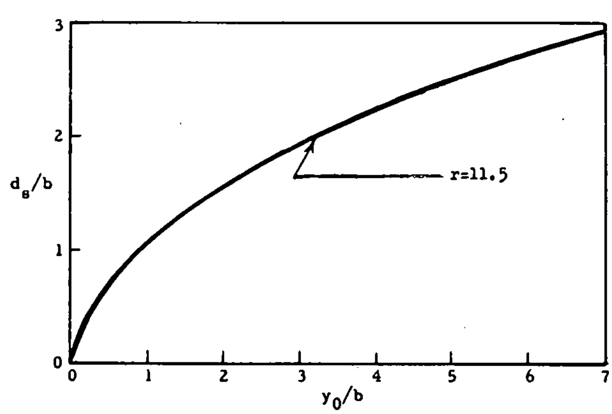


Figure C-11. Scour around basic bridge pier.

half-width of the pier, $b/2$, for the effective length, λ. The resulting relationship is shown in Figure C-11.

Similarly, the condition of no supply (clear-water scour) can be adapted to the pier and abutment as shown in Figures C-12 and C-13. The family of curves brings in the additional parameter τ_0'/τ_c, which in the analysis was assumed to be characteristic of a sand size; considerable judgment is necessary in extending the concept to cohesive soils. The parameter should be applicable to the determination of riprap size buried various depths below the stream bed. The riprap, however, should not be of a single size or there will be leaching through the voids of the layer. It is important also that the lateral extent of a riprap layer be sufficient so that the volume of the arrested scour hole will be approximately equal to that of the unarrested scour hole.

The analysis culminating in these relationships assumes a very simple geometry; most of the associated laboratory experiments were of equally simple geometry. However, some geometric variations have been studied in the laboratory, and these results permit the evaluation of multiplying factors. Table C-1 gives some coefficients that take into account the shape of the pier or abutment.

Figure C-14 shows the effect of the angle of incidence of the embankment, the multiplying factor, K_θ, being less than unity for the more "streamlined" angles less than 90°. Figure C-15 shows the combined effect of the length-width ratio and the angle of attack for the pier, the multiplying factor, $K_{\alpha L}$, always being greater than unity and the effect of shape, K_s, being lost. A nongeometric factor is shown in Figure C-16, which gives a multiplying factor, K_T, for different modes of sediment-movement-bed load, light to moderate suspended load, heavy suspended load. It should be noted that the size of sediment to be considered is that of the bed material to be scoured, not the so-called "wash" load.

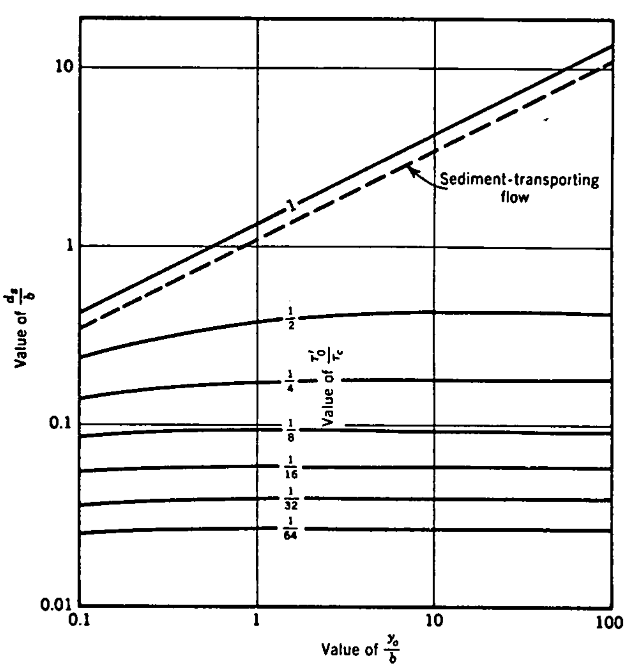


Figure C-12. Clear-water scour at a pier.

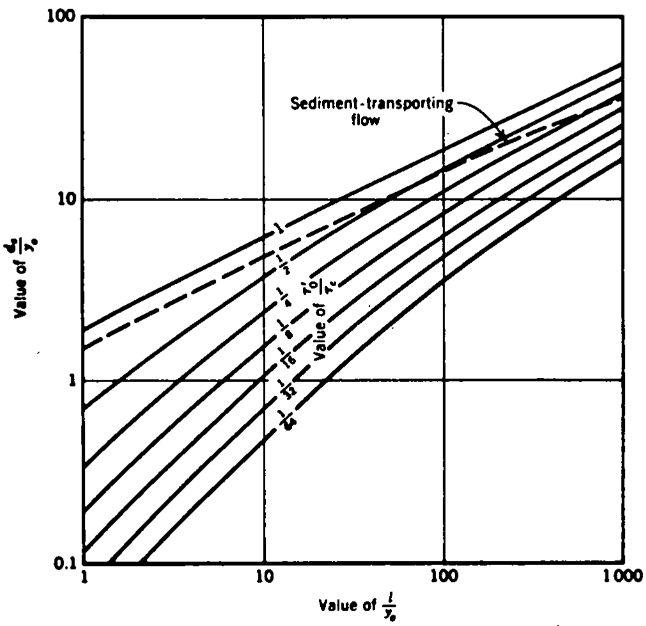


Figure C-13. Clear-water scour at an abutment.

TABLE C-1

SHAPE COEFFICIENT, K_s, FOR PIERS *
AND ABUTMENTS

OBSTRUCTION TYPE	NOSE FORM	LENGTH-WIDTH RATIO	K_s
Abutment:			
Vertical wall			1.00
Wing wall			0.90
Spillthrough			0.80
Pier	Rectangular		1.00
	Semicircular		0.90
	Elliptic	2:1	0.80
		3:1	0.75
	Lenticular	2:1	0.80
		3:1	0.70

* To be used only for piers aligned with flow.

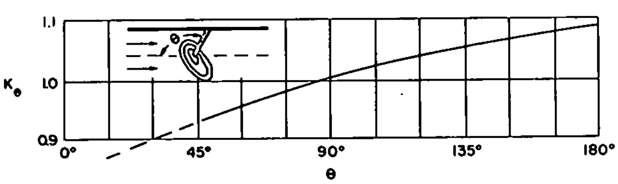


Figure C-14. Design factors for the angle of incidence.

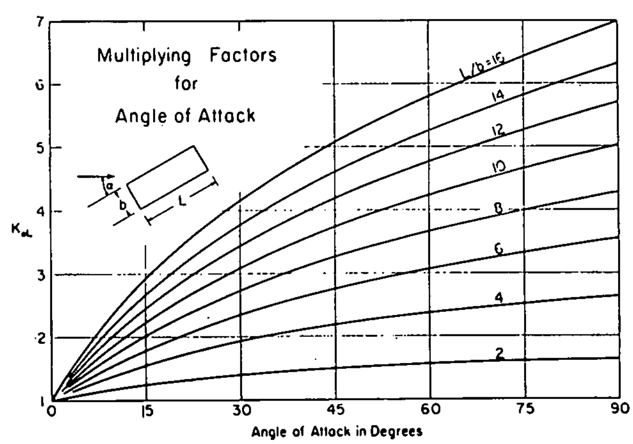


Figure C-15. Design factors for piers not aligned with the flow.

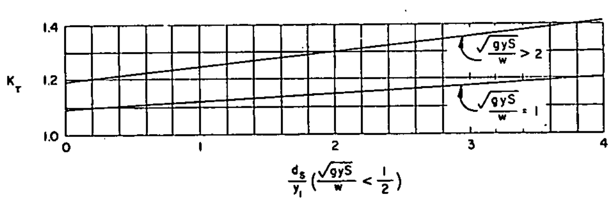


Figure C-16. Design factors for changes in the mode of movement.

APPENDIX D

AGENCIES RESPONDING TO QUESTIONNAIRE

The following is a list of the agencies responding to the 1969 survey on present practice and research.

PRESENT PRACTICE

State Highway Departments

Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Vermont
Virginia
Washington
West Virginia
Wisconsin

Governmental Agencies

U.S. Bureau of Public Roads

U.S. Bureau of Reclamation

U.S. Army Corps of Engineers

Contractors

Austin Bridge Company

Brown & Root

T. L. James Company

Peter Kiewit Sons

Morrison-Knudson Company

H. B. Zachary

Railroads

Atchison, Topeka and Santa Fe
Baltimore & Ohio
Boston & Maine
Chesapeake & Ohio
Chicago, Burlington & Quincy
Chicago, Milwaukee, St. Paul and Pacific
Chicago and North Western
Chicago, Rock Island and Pacific
Erie Lackawanna Railway
Great Northern
Illinois Central Railroad
Louisville & Nashville
Missouri-Kansas-Texas
Northern Pacific
Reading Railway System
St. Louis Southwestern
Southern Railway System
Spokane, Portland & Seattle

Consulting Engineers

Bechtel Corporation
Dames & Moore
Edwards and Kelcey
Fay, Spofford & Thorndike
J. E. Greiner Company
Hardesty & Hanover
Howard, Needles, Tammen & Bergendoff
Madigan-Hyland
Modjeski and Masters
Parsons, Brinckerhoff, Quade & Douglas
Shannon & Wilson
Sverdrup & Parcel and Associates
Tippetts-Abbett-McCarthy-Stratton
Whitman, Requardt & Associates
Woodward-Clyde & Associates

Other

Canadian Good Roads Association

RESEARCH

University of Alberta
Colorado State University
University of Illinois
University of Iowa
Iowa State University of Science & Technology
Johns Hopkins University
National Hydraulics Laboratory (France)
National University of Mexico
Swedish Geotechnical Institute
Swiss Federal Institute of Technology
U.S. Department of Agriculture
U.S. Army Waterways Experiment Station
U.S. Bureau of Public Roads

APPENDIX E

QUESTIONS USED AS INTERVIEW GUIDE

1. What preliminary field investigations are made with respect to potential scour at bridge waterways?
2. To what extent is scouring around bridge piers and abutments a problem for structures under your jurisdiction?
3. What do you regard as the primary reasons for the occurrence of scour problems?
   (a) Subsoil characteristics?
   (b) Design procedures?
   (c) Maintenance procedures?
   (d) Other?
4. How is the depth and extent of probable scour around bridge piers and abutments estimated? Outline design procedures.
5. What procedures are used for estimating extent of probable scour at temporary cofferdams or other obstructions?
6. What steps are taken in the orderly development of the proper waterway opening required at a bridge site?
7. What specific design techniques are incorporated to insure maximum protection of piers and abutments against scour?
8. Is there a program currently in effect to monitor scour at bridge substructure units? Describe this program or any contemplated one.
9. Do you have a program for inspection for scour?
   (a) Is there a systematic inspection schedule? Explain.
   (b) Are divers used for the underwater inspections?
   (c) Is any special instrumentation used?
   (d) When is the inspection for scour around piers and abutments performed—during flooding, immediately following, or at periods of normal stream level?
10. What are some of the corrective measures employed when scour develops beneath structures?
11. Is any research concerning scour at bridge piers and abutments being conducted or contemplated? Please elaborate.
12. What has been your general experience with respect to the amount of additional construction cost necessitated by specific attempts to properly design for prevention of scour at bridge piers and abutments?
13. Assuming scour has been detected, at what administrative level is this reported and acted on?
14. What has been your experience with respect to scour during construction with cofferdams and sand islands?
15. What has been your experience with the use of willow mattresses in connection with pier construction, and scour?
16. What restraints, if any, are placed on use of the floodplain upstream and downstream and the stream above and below the bridge site, with respect to sources of borrow for embankment construction or quarrying of materials?
17. Please explain the extent of collaboration among hydraulics, bridge design, and foundation engineers and others, in field and office studies in estimating extent of scour at a bridge.
18. Do you have case histories of failures or troublesome situations arising from scour, that could be released for their value to bridge and highway engineers? Please describe in detail.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Rep. No.	*Title*
—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj. 4-3(2)), 81 p., $1.80
1	Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Proj. 6-8), 56 p., $2.80
2	An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1.80
2A	Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00
3	Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Proj. 3-5), 36 p., $1.60
4	Non-Chemical Methods of Snow and Ice Control on Highway Structures (Proj. 6-2), 74 p., $3.20
5	Effects of Different Methods of Stockpiling Aggregates—Interim Report (Proj. 10-3), 48 p., $2.00
6	Means of Locating and Communicating with Disabled Vehicles—Interim Report (Proj. 3-4), 56 p. $3.20
7	Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Proj. 1-2), 29 p., $1.80
8	Synthetic Aggregates for Highway Construction (Proj. 4-4), 13 p., $1.00
9	Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Proj. 3-2), 28 p., $1.60
10	Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Proj. 1-4), 31 p., $2.80
11	Effect of Control Devices on Traffic Operations—Interim Report (Proj. 3-6), 107 p., $5.80
12	Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Proj. 4-3(1)), 47 p., $3.00
13	Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Proj. 2-5), 43 p., $2.80
14	Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Proj. 10-5), 32 p., $3.00
15	Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Proj. 4-3(2)), 66 p., $4.00
16	Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Proj. 6-3), 21 p., $1.60
17	Development of Guidelines for Practical and Realistic Construction Specifications (Proj. 10-1), 109 p., $6.00
18	Community Consequences of Highway Improvement (Proj. 2-2), 37 p., $2.80
19	Economical and Effective Deicing Agents for Use on Highway Structures (Proj. 6-1), 19 p., $1.20
20	Economic Study of Roadway Lighting (Proj. 5-4), 77 p., $3.20
21	Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Proj. 1-5), 30 p., $1.40
22	Factors Influencing Flexible Pavement Performance (Proj. 1-3(2)), 69 p., $2.60
23	Methods for Reducing Corrosion of Reinforcing Steel (Proj. 6-4), 22 p., $1.40
24	Urban Travel Patterns for Airports, Shopping Centers, and Industrial Plants (Proj. 7-1), 116 p., $5.20
25	Potential Uses of Sonic and Ultrasonic Devices in Highway Construction (Proj. 10-7), 48 p., $2.00
26	Development of Uniform Procedures for Establishing Construction Equipment Rental Rates (Proj. 13-1), 33 p., $1.60
27	Physical Factors Influencing Resistance of Concrete to Deicing Agents (Proj. 6-5), 41 p., $2.00
28	Surveillance Methods and Ways and Means of Communicating with Drivers (Proj. 3-2), 66 p., $2.60
29	Digital-Computer-Controlled Traffic Signal System for a Small City (Proj. 3-2), 82 p., $4.00
30	Extension of AASHO Road Test Performance Concepts (Proj. 1-4(2)), 33 p., $1.60
31	A Review of Transportation Aspects of Land-Use Control (Proj. 8-5), 41 p., $2.00
32	Improved Criteria for Traffic Signals at Individual Intersections (Proj. 3-5), 134 p., $5.00
33	Values of Time Savings of Commercial Vehicles (Proj. 2-4), 74 p., $3.60
34	Evaluation of Construction Control Procedures—Interim Report (Proj. 10-2), 117 p., $5.00
35	Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests (Proj. 1-3(3)), 117 p., $5.00
36	Highway Guardrails—A Review of Current Practice (Proj. 15-1), 33 p., $1.60
37	Tentative Skid-Resistance Requirements for Main Rural Highways (Proj. 1-7), 80 p., $3.60
38	Evaluation of Pavement Joint and Crack Sealing Materials and Practices (Proj. 9-3), 40 p., $2.00
39	Factors Involved in the Design of Asphaltic Pavement Surfaces (Proj. 1-8), 112 p., $5.00
40	Means of Locating Disabled or Stopped Vehicles (Proj. 3-4(1)), 40 p., $2.00
41	Effect of Control Devices on Traffic Operations (Proj. 3-6), 83 p., $3.60
42	Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60
43	Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5), 38 p., $2.00
44	Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40
45	Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40
46	Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60
47	Accident Rates as Related to Design Elements of Rural Highways (Proj. 2-3), 173 p., $6.40
48	Factors and Trends in Trip Lengths (Proj. 7-4), 70 p., $3.20
49	National Survey of Transportation Attitudes and Behavior—Phase I Summary Report (Proj. 20-4), 71 p., $3.20

* Highway Research Board Special Report 80.

Rep. No.	Title
50	Factors Influencing Safety at Highway-Rail Grade Crossings (Proj. 3-8), 113 p., $5.20
51	Sensing and Communication Between Vehicles (Proj. 3-3), 105 p., $5.00
52	Measurement of Pavement Thickness by Rapid and Nondestructive Methods (Proj. 10-6), 82 p., $3.80
53	Multiple Use of Lands Within Highway Rights-of-Way (Proj. 7-6), 68 p., $3.20
54	Location, Selection, and Maintenance of Highway Guardrails and Median Barriers (Proj. 15-1(2)), 63 p., $2.60
55	Research Needs in Highway Transportation (Proj. 20-2), 66 p., $2.80
56	Scenic Easements—Legal, Administrative, and Valuation Problems and Procedures (Proj. 11-3), 174 p., $6.40
57	Factors Influencing Modal Trip Assignment (Proj. 8-2), 78 p., $3.20
58	Comparative Analysis of Traffic Assignment Techniques with Actual Highway Use (Proj. 7-5), 85 p., $3.60
59	Standard Measurements for Satellite Road Test Program (Proj. 1-6), 78 p., $3.20
60	Effects of Illumination on Operating Characteristics of Freeways (Proj. 5-2) 148 p., $6.00
61	Evaluation of Studded Tires—Performance Data and Pavement Wear Measurement (Proj. 1-9), 66 p., $3.00
62	Urban Travel Patterns for Hospitals, Universities, Office Buildings, and Capitols (Proj. 7-1), 144 p., $5.60
63	Economics of Design Standards for Low-Volume Rural Roads (Proj. 2-6), 93 p., $4.00
64	Motorists' Needs and Services on Interstate Highways (Proj. 7-7), 88 p., $3.60
65	One-Cycle Slow-Freeze Test for Evaluating Aggregate Performance in Frozen Concrete (Proj. 4-3(1)), 21 p., $1.40
66	Identification of Frost-Susceptible Particles in Concrete Aggregates (Proj. 4-3(2)), 62 p., $2.80
67	Relation of Asphalt Rheological Properties to Pavement Durability (Proj. 9-1), 45 p., $2.20
68	Application of Vehicle Operating Characteristics to Geometric Design and Traffic Operations (Proj. 3-10), 38 p., $2.00
69	Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects (Proj. 10-2A), 58 p., $2.80
70	Social and Economic Factors Affecting Intercity Travel (Proj. 8-1), 68 p., $3.00
71	Analytical Study of Weighing Methods for Highway Vehicles in Motion (Proj. 7-3), 63 p., $2.80
72	Theory and Practice in Inverse Condemnation for Five Representative States (Proj. 11-2), 44 p., $2.20
73	Improved Criteria for Traffic Signal Systems on Urban Arterials (Proj. 3-5/1), 55 p., $2.80
74	Protective Coatings for Highway Structural Steel (Proj. 4-6), 64 p., $2.80
74A	Protective Coatings for Highway Structural Steel—Literature Survey (Proj. 4-6), 275 p., $8.00
74B	Protective Coatings for Highway Structural Steel—Current Highway Practices (Proj. 4-6), 102 p., $4.00
75	Effect of Highway Landscape Development on Nearby Property (Proj. 2-9), 82 p., $3.60

Rep. No.	Title
76	Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements (Proj. 1-5(2)), 37 p., $2.00
77	Development of Design Criteria for Safer Luminaire Supports (Proj. 15-6), 82 p., $3.80
78	Highway Noise—Measurement, Simulation, and Mixed Reactions (Proj. 3-7), 78 p., $3.20
79	Development of Improved Methods for Reduction of Traffic Accidents (Proj. 17-1), 163 p., $6.40
80	Oversize-Overweight Permit Operation on State Highways (Proj. 2-10), 120 p., $5.20
81	Moving Behavior and Residential Choice—A National Survey (Proj. 8-6), 129 p., $5.60
82	National Survey of Transportation Attitudes and Behavior—Phase II Analysis Report (Proj. 20-4), 89 p., $4.00
83	Distribution of Wheel Loads on Highway Bridges (Proj. 12-2), 56 p., $2.80
84	Analysis and Projection of Research on Traffic Surveillance, Communication, and Control (Proj. 3-9), 48 p., $2.40
85	Development of Formed-in-Place Wet Reflective Markers (Proj. 5-5), 28 p., $1.80
86	Tentative Service Requirements for Bridge Rail Systems (Proj. 12-8), 62 p., $3.20
87	Rules of Discovery and Disclosure in Highway Condemnation Proceedings (Proj. 11-1(5)), 28 p., $2.00
88	Recognition of Benefits to Remainder Property in Highway Valuation Cases (Proj. 11-1(2)), 24 p., $2.00
89	Factors, Trends, and Guidelines Related to Trip Length (Proj. 7-4), 59 p., $3.20
90	Protection of Steel in Prestressed Concrete Bridges (Proj. 12-5), 86 p., $4.00
91	Effects of Deicing Salts on Water Quality and Biota —Literature Review and Recommended Research (Proj. 16-1), 70 p., $3.20
92	Valuation and Condemnation of Special Purpose Properties (Proj. 11-1(6)), 47 p., $2.60
93	Guidelines for Medial and Marginal Access Control on Major Roadways (Proj. 3-13), 147 p., $6.20
94	Valuation and Condemnation Problems Involving Trade Fixtures (Proj. 11-1(9)), 22 p., $1.80
95	Highway Fog (Proj. 5-6), 48 p., $2.40
96	Strategies for the Evaluation of Alternative Transportation Plans (Proj. 8-4), 111 p., $5.40
97	Analysis of Structural Behavior of AASHO Road Test Rigid Pavements (Proj. 1-4(1)A), 35 p., $2.60
98	Tests for Evaluating Degradation of Base Course Aggregates (Proj. 4-2), 98 p. $5.00
99	Visual Requirements in Night Driving (Proj. 5-3), 38 p., $2.60
100	Research Needs Relating to Performance of Aggregates in Highway Construction (Proj. 4-8), 68 p., $3.40
101	Effect of Stress on Freeze-Thaw Durability of Concrete Bridge Decks (Proj. 6-9), 70 p., $3.60
102	Effect of Weldments on the Fatigue Strength of Steel Beams (Proj. 12-7), 114 p., $5.40
103	Rapid Test Methods for Field Control of Highway Construction (Proj. 10-4), 89 p., $5.00
104	Rules of Compensability and Valuation Evidence for Highway Land Acquisition (Proj. 11-1), 77 p., $4.40

Rep. No.	*Title*
105	Dynamic Pavement Loads of Heavy Highway Vehicles (Proj. 15-5), 94 p., $5.00
106	Revibration of Retarded Concrete for Continuous Bridge Decks (Proj. 18-1), 67 p., $3.40

Synthesis of Highway Practice

1	Traffic Control for Freeway Maintenance (Proj. 20-5, Topic 1), 47 p., $2.20
2	Bridge Approach Design and Construction Practices (Proj. 20-5, Topic 2), 30 p., $2.00
3	Traffic-Safe and Hydraulically Efficient Drainage Practice (Proj. 20-5, Topic 4), 38 p., $2.20
4	Concrete Bridge Deck Durability (Proj. 20-5, Topic 3), 28 p., $2.20
5	Scour at Bridge Waterways (Proj. 20-5, Topic 5), 37 p., $2.40

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by President Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U. S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Federal Highway Administration, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.

HIGHWAY RESEARCH BOARD
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue Washington, D. C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970

000015
MATERIALS ENGR

IDAHO DEPT OF HIGHWAYS
P O BOX 7129
BOISE ID 83707