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1998 Scanning Review of European Practice for Bridge Scour and Stream Instability Countermeasures

This digest summarizes the findings of an international technology scanning review conducted with the support of NCHRP Project 20-36, "Highway Research and Technology—International Information Sharing." The scanning review team consisted of representatives from U.S. federal and state agencies as well as the private sector. Peter F. Lagasse, Report Facilitator for the review, prepared the digest.

SUMMARY

INTRODUCTION

This digest describes the findings of the 1998 International Scanning Review of European Practice for Bridge Scour and Stream Instability Countermeasures organized under the auspices of FHWA's International Outreach Program and the American Association of State Highway and Transportation Officials (AASHTO) through the National Cooperative Highway Research Program (NCHRP). This review was undertaken to review and document innovative techniques used to mitigate the effects of scour and stream instability at bridges, evaluate these techniques for potential application in the United States, and share information on U.S. practice with European counterparts.

This review was performed by a team of representatives from FHWA, the state DOTs of California, Illinois, Maryland, Minnesota, Oregon, and South Carolina, universities, and the private sector. The review included visits to highway research institutes, hydraulic research laboratories, and field sites in Switzerland, Germany, the Netherlands, and the United Kingdom.

Although the review concentrated on bridge scour and stream instability countermeasures, the scanning review team members' inquiries were wide-ranging and included basic scour technology for evaluation and design, laboratory and field research programs, environmental issues, and bioengineering techniques.

GENERAL OBSERVATIONS

Design Philosophy

The general design approach in Switzerland, Germany, and the Netherlands is to prevent scour from occurring or move scour away from the structure by including scour and stream instability countermeasures in the initial design and construction of their bridges. In general, these countries believe that they do not have a significant bridge scour problem, largely because of this design approach. The bridge scour problem in the United Kingdom is similar to that faced in the United States. Both countries are applying the latest scour technology to the design of new bridges, but both face significant problems with scour and stream instability at thousands of bridges in an aging infrastructure.

Risk Analysis

Some form of risk analysis is used to determine the level of effort and investment in countermeasure design and installation in all countries visited. For example, the Netherlands uses both a regional risk analysis (considering such factors as distance from the coast and vulnerability to storm

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surge) and a detailed analysis of the risk of failure of individual components of a project. These factors influence the decision on investment in scour countermeasures.

Environmental Policy

Environmental impacts are considered for scour and stream instability countermeasure selection, design, and installation in all countries visited. In general, the approach is to emphasize environmental enhancement and sustainability, without creating an undue risk to lives and property in applying environmental policy to structures in a riverine system.

River Geomorphology

All four countries in Europe recognize the value of a geomorphic analysis in bridge and countermeasure design. In the United Kingdom, in particular, research in applying geomorphic reconnaissance techniques to river engineering problems has produced useful and practical guidance for the hydraulic engineer. Such techniques support geomorphic classification of a river system and permit a detailed investigation of form and process for critical reaches where instability could affect bridge design or countermeasure selection, design, and maintenance.

Scour Prediction

Although investigating improved scour prediction techniques was not the primary purpose of the scanning review, methods to calculate scour, particularly in complex flow situations, were of interest to the scanning review team members. In Europe, the influence of turbulence in relation to the structure (e.g., bridges and storm surge barriers) and the time rate of scour are considered key factors for estimating scour potential and designing scour countermeasures.

The problems of estimating scour at wide piers, the time rate of scour (particularly in cohesive materials) and the interaction of the various scour components are recognized as being among the most pressing U.S. research needs in scour. Comprehensive scour manuals obtained by the scanning review team members include techniques to analyze several of these problems.

Modeling

Both physical hydraulic modeling in a laboratory and numerical computer modeling are among the standard techniques available to analyze the scour problem and design countermeasures. In Europe it is much more likely that physical modeling, often in conjunction with computer modeling, will be used as an integral part of the hydraulic design process for bridge foundations and countermeasures than is typical in the United States.

A major effort is underway in Europe to develop 1-, 2-, and 3-dimensional computer models with hydrodynamic, sediment transport, and, in some cases, morphologic capabilities. As an initial reaction, it appears that U.S. 1- and 2-dimensional hydrodynamic modeling capabilities to support scour predictions and countermeasures design are comparable with what is currently available in Europe.

Inspection and Monitoring

Most of the countries visited have initiated efforts to develop a bridge inspection or scour evaluation program comparable to the National Bridge Inspection Standards (NBIS) in the United States. In Germany, the Federal Highway Research Institute (BAST) is investigating the use of the FHWA PONTIS bridge management system.

An effort comparable to NCHRP Project 21-3 has been made in the United Kingdom to develop fixed instrumentation for measuring and monitoring scour at bridge piers and abutments. This resulted in the patented Wallingford “Tell-Tail” device, which was installed on several railroad bridges following a catastrophic railroad bridge failure.

In none of the four countries was technology available to determine the characteristics of unknown bridge foundations (i.e., foundations for which design or as-built drawings do not exist). In the United Kingdom, there are numerous unknown foundation bridges and the problem is considered as serious as it is in the United States.

OBSERVATIONS ON SPECIFIC COUNTERMEASURES

Riprap

The use of riprap (i.e., armor stone in combination with a geotextile or granular filter) is by far the most common scour and stream instability countermeasure in all countries visited in Europe. Its availability, economy, ease of installation, and flexibility are considered highly desirable characteristics in all four countries visited. As a result, considerable effort has been devoted to techniques for determining size, gradation, layer thickness and horizontal extent, filters, and placement techniques and equipment for revetment and coastal applications. European hydraulic engineers consider riprap an effective and permanent countermeasure against channel instability and scour, including local scour at bridge piers.

Great care is taken in placing the riprap at critical locations, and, in many cases, stones are placed individually in the riprap matrix. Highly specialized equipment has been developed by construction contractors in Europe for placing riprap, particularly for coastal installations. The use of bottom dump or side dump pontoons (barges) is common in both Germany and the Netherlands. Some of the smaller pontoon systems, particularly the bottom dump pontoons developed in Germany, could be used to place riprap in water at larger bridges.

At the BAW in Germany, the scanning review team members observed wave tank testing of prototype scale partially grouted riprap. In general, the objective is to increase the stability of the riprap without sacrificing all of the flexibility. Contractors in Germany have developed techniques and equipment to achieve the desired grout coverage and the right penetration. Current guidance in the United States tends to discourage the use of grouted riprap. However, BAW engineers believe that partial grouting, if done correctly, will ensure that the riprap retains sufficient flexibility while enhancing stability.

Filters

As in the United States, a properly designed geotextile or granular filter is considered essential to the success of riprap and most other countermeasures on sand or fine-grained material. In Germany and the Netherlands, a significant investment has been made in the development and testing of geosynthetic materials, and innovative installation techniques have been developed that could find application for bridge pier and abutment countermeasures in the United States.

Geotextile containers (large sand bags) made of mechanically bonded non-woven fabrics up to 1.25 cubic m in volume have been used to provide a filter layer for riprap installation at several large projects in Germany. The containers are placed in layers using a side-dump pontoon. Riprap is then placed over the layer of geotextile containers. A geotextile bag filter and riprap protection were used in combination as a countermeasure against pier scour at a new bridge on the Peena River in Germany.

Three countries (i.e., Germany, the Netherlands, and the United Kingdom) use fascine mats, a very old, traditional approach for scour protection, to place a geotextile filter in deep water. The fascines consist of a matrix of willow or other natural material woven in long bundles (15 to 20 cm in diameter) to form a matrix assembled over a layer of woven geotextile. The fascine mattress, sometimes called a “sinker mat,” is floated into position and sunk into place by dropping riprap-size stone on it from a barge.

River Training

River training and stabilization techniques against lateral channel migration in the major navigable waterways of Europe are similar to those employed by the U.S. Army Corps of Engineers on navigable waterways in the United States (e.g., the Mississippi, Ohio, and Missouri river systems). Groins and jetties projecting roughly perpendicular to the river bank, dikes placed parallel to the river bank, or revetment placed on the river bank are the most common river training works in Europe.

Given that river training has been ongoing on Europe’s navigable rivers (or on canals in the Netherlands) for hundreds of years, there are few unprotected reaches of river. Thus, lateral instability because of river meander is rare and is not considered a threat to bridges.

Riverbed Degradation

Sills, grade control structures, low check dams, or weirs constructed of various materials are commonly used in Europe to protect against vertical channel instability (degradation) as they are in the United States. In Germany, the approach to the problem of degradation on the Rhine River has involved sediment management on a large scale. The problems are generally related to a deficiency in the supply of sediment to a river reach or river system. As a result, a systemwide sediment management program has evolved that involves as one component, an attempt to replenish the sediment supply by “feeding the Rhine.”

The Swiss also recognize the effects of sediment deficiency on river system stability. Prior to 1970, gravel mining (or harvesting) from rivers was allowed in Switzerland, but when scour problems were noted in adjacent reaches, the practice was restricted. Currently, the allowed quantity of gravel extracted is fixed on the basis of the sediment regime of the river.

Alternative Countermeasures

Among the areas of particular interest to the scanning review team members during the scanning review were alternative countermeasures such as flow-altering devices or alternatives to riprap (particularly for the pier scour problem). The following paragraphs summarize some of the scanning review team members’ observations.

In 1987, the Swiss experienced a near catastrophic failure of a major highway bridge when the Reuss River migrated laterally and undermined the foundation of a bridge pier. The countermeasure system developed by the VAW/ETH laboratory included very large precast concrete prisms, triangular in cross section, placed individually as revetment. In lieu of smaller interlocking armor units that would be costly to fabricate, the decision was made to cast much larger prisms with a simple shape and use the mass of the prisms to protect against river bank scour. The economics of the tradeoffs between smaller, high-cost interlocking shapes for artificial riprap and simpler shapes with more mass are worth further consideration.

Recent laboratory testing by NCHRP, FHWA, and others in the United States indicates that when articulating mat products are used as a pier scour countermeasure, the joint between the mattress and the pier must be protected to prevent scour under the mat. The scanning review team members encountered two approaches to solving this problem that justify further evaluation.

Recent laboratory research by NCHRP, FHWA, and others in the United States has shown that flow-altering devices (e.g., scour collars, sacrificial piles, and guide vanes) are only marginally effective as countermeasures against pier scour. The scanning review team members did not encounter any successful applications of flow-altering devices as a pier scour countermeasure in any of the countries visited.

Protecting bridges from the accumulation of debris and predicting the increase in scour at a bridge caused by debris is a problem worldwide. The scanning review team members did not encounter any applications of "debris deflectors" or other devices at a bridge during the scanning review.

Bioengineering

Although bioengineering techniques are integrated with traditional engineering countermeasures for river system management in Europe, hydraulic engineers in all the countries visited would not recommend reliance on bioengineering countermeasures as the only countermeasure technique if there is risk of damage to property or a structure or if there is the potential for loss of life. A primary concern expressed was a lack of knowledge about the properties of the materials being used in relation to force and stress generated by flowing water and the difficulties in obtaining consistent performance from countermeasures relying on living materials.

APPLICATION TO U.S. PRACTICE

The scanning review team members identified several potential European bridge scour techniques that could improve U.S. practice. These techniques should be considered further by appropriate research funding agencies (e.g., TRB, NCHRP, FHWA, and state DOTs and other bridge owners) or agencies such as FHWA or AASHTO that establish transportation policy, code, guidelines, and specifications.

Techniques To Reduce Bridge Scour and To Enhance Stream Stability

- Conduct a thorough review of European literature on bridge scour and stream instability technology, particularly the comprehensive scour manuals obtained during the scanning review.
- Encourage increased use of risk analysis in the design and evaluation process including accepting a variable degree of protection depending on the importance of the structure.
- Adapt stream reconnaissance techniques to the evaluation of stream stability in the vicinity of highway structures, and continue to encourage a geomorphic approach for stream system analysis, bridge design, and countermeasure selection.
- Improve techniques to analyze and predict scour, particularly for complex flow situations (e.g., wide piers, pressure flow, debris, and the interaction of general and local scour components) by a more detailed evaluation of European practice.
- Investigate the characteristics of time rate of scour in non-cohesive and cohesive materials.
- Consider the applicability of sediment management as a strategy to counteract long-term riverbed degradation problems.

Countermeasure Techniques for Bridge Foundations

- Evaluate the economics of including scour and stream instability countermeasures in the initial construction of a bridge.
- Re-evaluate design and installation techniques for riprap, and reconsider its viability as a permanent countermeasure against pier scour.
- Evaluate and test European techniques for the design and installation of partially grouted riprap, and re-evaluate its applicability to United States practice.
- Evaluate and test the use of innovative techniques for placing filters under riprap and other countermeasures, including geotextile containers, geotextile mattresses, the use of fascine mats, and hydrodynamically sand tight filters.
- Investigate the economics of tradeoffs between smaller, high-cost interlocking shapes for artificial riprap and simpler shapes with more mass to resist hydraulic stress.
- Evaluate and test European techniques to prevent scour at the "joint" between articulating mattresses and a bridge pier when these products are used as a pier scour countermeasure.

Techniques To Address Environmental Issues

- Consider risk to the structure, lives, or property in applying environmental policy to bridge scour protection and countermeasures.
- Evaluate and test bioengineering and biotechnical engineering techniques as bridge scour countermeasures for situations where public safety considerations would not preclude their use.

RECOMMENDATIONS

The scanning review team members recommend that several elements of European practice be considered on a high-priority basis to improve U.S. capabilities to deal with stream instability and bridge scour problems. An implementation plan is also suggested to ensure that the technology acquisition activities initiated by the scanning review will continue and will be disseminated to bridge owners and their engineering staff.

High-Priority Recommendations

Riprap and Filters

Currently, policy in the United States considers riprap placed at bridge piers to be only a temporary countermea-

sure against pier scour, and guidance dictates that riprap placed at bridge piers must be monitored by periodic inspection or with fixed instruments. During the scanning review, it was apparent that the European counterparts consider riprap as a permanent pier scour countermeasure. The difference between U.S. and European practice is not necessarily derived from the availability of better techniques for sizing riprap, but rather from the higher standard of care and quality control in placing the stone and providing an appropriate filter on sandbed channels. In addition, European practice includes inspection and monitoring to verify that riprap is performing properly. European hydraulic engineers have developed innovative techniques for placing an effective filter beneath the riprap in flowing or deep water; these techniques include the use of such products as large geotextile sand containers, geotextile mattresses filled with granular filter material, and fascine sinker mats.

As state DOTs in the United States develop Plans of Action for their scour-critical bridges, improved techniques to use riprap effectively as a pier scour countermeasure could result in significant savings, particularly where the only alternative may be rehabilitation or replacement of the affected bridge. A high-priority evaluation of European practice for the design and installation of riprap with an appropriate filter as a permanent pier scour countermeasure is warranted.

Partially Grouted Riprap

Current practice in the United States discourages the use of grouted riprap, primarily because total grouting converts a flexible revetment material into a rigid mass susceptible to undermining and failure. Ongoing tests in Germany at BAW, experience on German inland waterways, and development of design guidance for partial bituminous and cement grouted riprap in the United Kingdom indicate that design guidelines and installation experience are available or are being developed in Europe. These European design guidelines, specifications, and installation techniques for partially grouted riprap should be investigated on a high-priority basis

Risk Analysis

The increased use of risk analysis in countermeasure selection and design and the use of techniques such as fault tree analysis could result in more economical design of bridge scour countermeasures. These concepts should be evaluated and disseminated, as appropriate, to bridge owners in the United States.

Scour Prediction

In the United States, the problems of estimating scour at wide piers, the time rate of scour in cohesive and non-cohesive materials, and the interaction of the various scour components are among the most pressing U.S. research needs in scour. Several scour manuals that provide a comprehensive treatment of the European approach to these problems were obtained by the scanning review team members. A detailed review of the Dutch *Scour Manual (8)* and other comprehensive treatments of the scour process is warranted.

Update of the FHWA HECs

In the United States, bridge scour technology is contained primarily in three FHWA HECs:

- HEC-18 Evaluating Scour at Bridges
- HEC-20 Stream Stability at Highway Structures
- HEC-23 Bridge Scour and Stream Instability Countermeasures

FHWA is revising and updating these manuals, with draft revisions scheduled for completion in October 1999. The scope of work for these revisions includes reviewing and evaluating the European literature on bridge scour and stream instability obtained by the scanning review team members during the scanning review. The FHWA Hydraulic Engineering Circulars and NHI training courses are the most efficient means of disseminating new technology to state DOTs and other bridge owners. Information gained from the countermeasures scanning review on European practice that does not require further research or laboratory or field testing should be incorporated into the current revisions of the HECs and training course materials.

Other activities to continue the technical contacts with counterparts in Europe and disseminate information gained during the scanning review are outlined in the Implementation Plan.

Implementation Plan

During the final scanning review team meeting, initial steps were taken to develop an implementation plan. Since returning from the scanning review, several implementation activities have been completed and others are being planned. The final section of this report summarizes these activities and suggests other implementation actions that should be considered for the future.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Of the more than 575,000 bridges in the national bridge inventory, approximately 84 percent are over water. Each year in the United States, highway bridge failures cost mil-

lions of dollars as a result of both direct costs necessary to replace or restore bridges and indirect costs related to disruption of transportation facilities. Of even greater consequence is the loss of life from bridge failures. Hydraulic factors (e.g., stream instability, degradation, contraction scour, and local scour) account for more U.S. bridge failures (approximately 60 percent) than all other factors combined.

Ongoing screening and evaluation of the vulnerability of the nations' highway bridges to scour by state DOTs have identified more than 18,000 bridges considered scour-critical (i.e., the bridge foundation is unstable for the calculated or observed scour condition) and in need of repair or replacement. Almost 100,000 bridges with unknown foundations have been identified. As state DOTs develop Plans of Action to identify adequate countermeasures for scour and stream instability, innovative, effective, and economical countermeasures should be considered for the design of new bridges and for repairing existing bridges.

Although considerable research has been done on the design of countermeasures for stream instability and scour problems in the United States, many have evolved through a trial-and-error process. With the publication of Hydraulic Engineering Circular 23 (HEC-23) (1997) *(1)*, FHWA took the initial step toward sharing countermeasure experience, selection, and design guidelines among Federal, state, and local highway agency personnel through the development of a countermeasure matrix. Although the scour countermeasure matrix will serve as FHWA interim guidelines on scour countermeasures for bridge owners to use in protecting bridge foundations from scour, the matrix represents, primarily, practice in the United States. There is a need to reach out to other countries to identify and evaluate countermeasures being used by bridge owners for potential implementation in the United States.

With this in mind, FHWA, AASHTO, and TRB sponsored a scanning review of European practice for bridge scour and stream instability countermeasures in October 1998. The countries selected—Switzerland, Germany, the Netherlands, and the United Kingdom—include a wide range of hydrologic, hydraulic, and geomorphic settings. Thus, the scanning review team members were able to observe and evaluate bridge scour and stream instability countermeasures on steep, coarse bed mountain streams (Switzerland); lower gradient, larger rivers (e.g., the Rhine in Germany); and tidal scour problems in the coastal zone (e.g., bridges and storm surge barriers in Germany and the Netherlands). In the United Kingdom, the scanning review team members were able to interact with researchers and practitioners, dealing with scour and stream instability problems on an aging rail and highway infrastructure where efforts are underway to determine the scope of the problem and evaluation, inspection, and design technology are being developed.

In the United States, bridge scour technology is contained primarily in three FHWA HECs:

- HEC-18 Evaluating Scour at Bridges (1995) *(2)*
- HEC-20 Stream Stability at Highway Structures (1995) *(3)*
- HEC-23 Bridge Scour and Stream Instability Countermeasures (1997) *(1)*

In addition, results of NCHRP Project 21-3 to develop, test, and evaluate fixed instrumentation that would be both technically and economically feasible for use in measuring or monitoring maximum scour depth at bridge piers and abutments are presented in three NCHRP reports:

- *NCHRP Report 396*, "Instrumentation for Measuring Scour at Bridge Piers and Abutments" (1997) *(4)*
- *NCHRP Report 397A,* "Sonar Scour Monitor" (1997) *(5)*
- *NCHRP Report 397B*, "Magnetic Sliding Collar Scour Monitor" (1997) *(6)*

Copies of the HEC manuals and NCHRP reports were provided to the host agency in each country visited as a basis for technology exchange and as an indication of current practice in the United States.

1.2 PURPOSE

The scanning review included visits to highway research institutes, hydraulic research laboratories, and field sites in the four countries visited. Scanning review objectives were as follows:

- Review and document innovative techniques used to mitigate the effects of scour and stream instability at bridges,
- Evaluate these techniques for potential application in the United States, and
- Share information on U.S. practice with counterparts in the countries visited.

Although the review concentrated on bridge scour and stream instability countermeasures, the scanning review team members' inquiries were wide ranging and included basic scour technology for evaluation and design, laboratory and field research programs, environmental issues, and bioengineering techniques.

In preparation for the scanning review, the scanning review team members developed a list of amplifying questions which were provided to the countries visited, to highlight the scanning review team members' areas of interest. This list (Appendix A of the Final Report, not included herein) included questions on the following topics:

- Bridge scour and stream stability technology (including basic technology, design, and inspection/training).

- Countermeasures for bridge scour and stream instability (including bridge scour countermeasures, stream instability countermeasures, flow-altering devices, rock riprap and alternatives, and instrumentation/monitoring),
- Laboratory and field research (including research programs, laboratory research, and field (site) research) and,
- Environmental issues and bioengineering.

1.3 SCANNING REVIEW TEAM MEMBERS

The scanning review involved representatives from FHWA, state DOTs (i.e., California, Illinois, Maryland, Minnesota, Oregon, and South Carolina), universities, and the private sector. The Scanning review team included a State Bridge Engineer and three members of the AASHTO Task Force on Hydraulics and Hydrology. The list of scanning review team members follows:

Don Flemming (Co-Chairman)	State Bridge Engineer Minnesota Department of Transportation
Jorge E. Pagan-Ortiz (Co-Chairman)	Hydraulics Engineer Office of Engineering, Bridge Division, FHWA
Catherine Avila	Senior Bridge Engineer CALTRANS
Jean-Louis Briaud	Professor, Department of Civil Engineering Texas A and M University
David W. Bryson	Hydraulics Engineer Oregon Department of Transportation
Daniel Ghere	Hydraulics Engineer Illinois Department of Transportation
William H. Hulbert	Hydraulics Engineer South Carolina Department of Transportation
J. Sterling Jones	Research Hydraulics Engineer Office of Engineering Research and Development, FHWA
Andrzej J. Kosicki	Bridge Hydraulics Engineer Maryland State Highway Agency
Peter F. Lagasse (Report Facilitator)	Senior Vice President Ayres Associates
Curtis Monk	Bridge Engineer FHWA, Iowa Division Office
Arthur Parola, Jr.	Associate Professor, Department of Civil and Environmental Engineering, University of Louisville

Brief biographical sketches of scanning review team members are provided in Appendix B of the Final Report but are not included herein.

1.4 ITINERARY AND APPROACH

The scanning review team members departed the United States on October 16, 1998, and convened in Zurich, Switzerland, on October 17, 1998. The itinerary and primary host agency at each location were as follows:

Zurich, Switzerland
October 16-20, 1998
Laboratory of Hydraulics, Hydrology and Glaciology (VAW); Swiss Federal Institute of Technology (ETH)

Karlsruhe, Germany
October 21, 1998
Federal Waterways Engineering and Research Institute (BAW)

Rhine River—Koblenz to Mainz, Germany
October 22, 1998
Federal Waterways Engineering and Research Institute (BAW) and Federal Highway Research Institute (BAST)

Bergisch-Gladbach (Cologne), Germany
October 23, 1998
Federal Highway Research Institute (BAST)

The Hague, the Netherlands
October 24-25, 1998
Mid-Tour Scanning Review Team Meeting

Eastern Scheldt Barrier, the Netherlands
October 26, 1998
Directorate General of Public Works and Water Management

Delft Hydraulics, Delft and New Waterway Storm Surge Barrier, Rotterdam, the Netherlands
October 27, 1998
Delft Hydraulics

Wallingford, United Kingdom
October 28-29, 1998
H.R. Wallingford

Nottingham, United Kingdom
October 30, 1998
University of Nottingham

London, United Kingdom
October 31 - November 1, 1998
Final Scanning Review Team Meeting

A list of key contacts at each organization visited is provided as Appendix A of this digest; acronyms are identified in Appendix B of this digest.

Visits were made to national research institutes or directorates; federal, university, and private hydraulic research

laboratories; and field sites. A typical visit began with a presentation by the U.S. scanning review team (Co-chair and facilitator) on the magnitude of the scour problem in the United States, current technologies, and primary areas of interest. This was generally followed by a series of presentations by host agency professionals or invited speakers addressing issues raised in the amplifying questions. Ample time was available for questions from scanning review team members as well as group debate and dialog.

At hydraulic laboratories, the scanning review team members went on guided tours of facilities, concentrating on bridge scour modeling and related testing apparatus. The visits with several agencies also included discussion and demonstrations of hydraulic computer modeling capabilities. Field site visits included the Koblenz-to-Mainz reach of the Rhine River in Germany (to observe and discuss extensive river training works, bank protection, and bridge scour countermeasures) and both the Eastern Scheldt and Rotterdam New Waterway storm surge barriers in the Netherlands.

The mid-tour scanning review team meeting provided the opportunity to summarize the results of discussions in Switzerland and Germany, evaluate the response to the amplifying questions, and identify areas of particular interest for the Netherlands and the United Kingdom. The final scanning review team meeting was used to consolidate and prioritize findings, discuss applications of technology to U.S. practice, and develop a preliminary implementation plan.

1.5 REPORT FORMAT

Chapter 2 presents general observations related to scour and stream instability technology and observations on specific countermeasures in the four countries visited. Chapter 3 suggests applications to U.S. practice in the categories identified in the amplifying questions (Appendix A of the final report). Finally, Chapter 4 contains recommendations on high-priority technology that could significantly affect U.S. practice, as well as an Implementation Plan for both immediate and long-range activities that would continue the dialog initiated during the scanning review and contribute to phasing new technology into U.S. practice.

Appendix C of this digest cites references used in this digest, and Appendix D of this digest summarizes design methodology for selected topics.

CHAPTER 2

OBSERVATIONS AND DISCUSSION

2.1 GENERAL OBSERVATIONS

2.1.1 European Scour Manuals and Literature

During the scanning review, several recently published (or draft) documents were obtained that summarize bridge scour and countermeasure technology in the countries visited. These documents may enhance basic U.S. scour technology and do suggest several potentially useful countermeasure design and installation techniques. Other relevant articles and publications are cited in the sections that follow. Comprehensive manuals or scour-related documents include the following:

- Hints on promoting the stability of structures in water with recommendations for the preservation and maintenance of existing structures and tips for the construction of new structures recently issued (1998) by the Swiss Federal Offices of Highways, of Transport, and of Water Management and Swiss Federal Railways *(7)*.
- Recently published (1997) *Scour Manual* by hydraulic engineers of Delft Hydraulics and the Ministry of Transport, Public Works and Water Management in the Netherlands *(8)*
- Handbook 47 for Bridge Scour Assessment prepared by the British Railways Board *(9)*
- Railtrack Southern standards and procedures manual for "Managing the Danger to the Railway from Flooding and Tidal Action" *(10)*
- *Scour Assessment Comparison* prepared for British Railtrack by Jeremy Benn and Associates *(11)*
- Course notes on scour risk assessment and protection design prepared for British Railtrack by Jeremy Benn and Associates *(12)*
- Draft Advice Notice on assessment of scour at highway bridges being prepared for the Highways Agency in the United Kingdom *(13)*
- River and channel revetment design manual published recently by the H.R. Wallingford Laboratory in the United Kingdom *(14)*
- Waterway bank protection manual prepared by the British Environment Agency *(15)*
- A new publication on dikes and revetments by Pilarczyk in the Netherlands *(16)*
- Engineers in all four countries visited referred to a manual on the use of rock in hydraulic engineering (*CUR Report #169*) as an extremely important reference book *(17)*

On the subject of river geomorphology and channel stability, several manuals and handbooks were obtained:

- Interim guidelines on design of straight and meandering compound channels prepared by H.R. Wallingford and others for the British National Rivers Authority *(18)*
- Practical guide to river geomorphology prepared by the British National Centre for Risk Analysis and Options Appraisal *(19)*
- *Stream Reconnaissance Handbook* prepared by C.R. Thorne, Department of Geography, University of Nottingham, United Kingdom *(20)*

- Recently published collection of papers on applied fluvial geomorphology for river engineering and management, edited by Thorne, Hey, and Newson from the United Kingdom *(21)*

2.1.2 Design Philosophy

The general design approach in Switzerland, Germany, and the Netherlands is to prevent scour from occurring or move scour away from the structure by including scour and stream instability countermeasures in the initial design and construction of their bridges. In general, these countries believe that they do not have a significant bridge scour problem, largely because of this design approach. The fact that their major navigable waterways and canals have been stabilized by extensive river training works contributes to the success of this approach.

When designing hydraulic structures in the Netherlands, the following aspects are considered *(8, 16, 22)*. (This approach appears to be representative of European practice in general):

- **Function of the structure**—erosion as such is not the problem as long as the structure can fulfill its function.
- **Physical environment**—the structure should offer the required degree of protection against hydraulic loading, with an acceptable risk and, when possible, meet the requirements resulting from landscape, recreational, and ecological viewpoints.
- **Construction method**—construction costs should be minimized to an acceptable level and legal restrictions must be adhered to.
- **Operation and maintenance**—it must be possible to manage and maintain the hydraulic structure.

The cost of construction and maintenance is generally considered a controlling factor in determining the type of structure to be used. Therefore, the starting points for the design are carefully examined in cooperation with the future manager of the project. Most projects dealing with hydraulic structures are considered multidisciplinary in character (as characterized by all relevant interactions between the soil, water, and structure) and may require combined hydraulic, geotechnical, and structural analyses. These interactions are often presented in a diagram similar to Figure 1.

Increased demand for reliable design of protective structures in the Netherlands has stimulated preparation of an improved design policy (especially regarding safety aspects) and development of more reliable technical design methods and design codes. The proper engineering strategy to be followed is based on the total balance of the possible effects of the countermeasures for the area considered, including environmental issues and economic effects. It is part of the engineer's philosophy to minimize the negative effects of the solution chosen *(22)*.

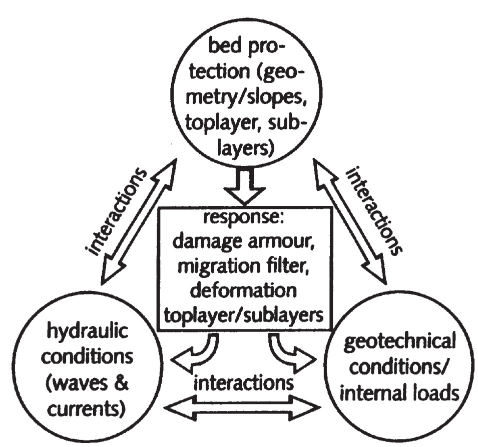

Figure 1. Soil-water-structure interaction (SOWAS concept) (8, 22).

The bridge scour problem in the United Kingdom is similar to that faced in the United States. Both countries are applying the latest scour technology to the design of new bridges, but both face significant problems with scour and stream instability at thousands of bridges in an aging infrastructure. As a result of a catastrophic railroad bridge failure with fatalities at Glanrhyd in 1987, Railtrack has taken the lead in developing scour assessment techniques and countermeasures in the United Kingdom *(9, 10, 11, 12)*. The British Highways Agency has recently developed an Advice Note for the assessment of scour at highway bridges *(13)*.

In Europe, in general *(16)*, and the United Kingdom, specifically *(14)*, there are two principal alternative approaches to the design of erosion and scour protection works: deterministic and probabilistic. In the deterministic approach, the worst conditions of loading are determined and the system is designed to withstand such loads with a certain margin of safety. This is a simpler but usually more conservative approach than the approach based on probabilistic considerations. Probabilistic design requires a statistical analysis of the various loads (i.e., the estimation of the probability of occurrence of loads and combinations of loads that may lead to the failure of the erosion or scour protection system). This approach involves the consideration of several scenarios. Its higher complexity renders it more suitable for major protection schemes, particularly those involving extreme wave heights. In most river situations, a deterministic design is usually suitable *(14)*.

Design procedures are generally derived for conditions at the threshold of movement and, therefore, stable sizes are determined for very limited instability (e.g., a revetment should ensure that practically no damage will occur). A recent design trend, however, has emerged that allows partial failure to occur. This can be suitable for situations where conservative hydraulic loadings are adopted, monitoring is frequent, a limited amount of damage is acceptable, or combinations thereof *(14)*.

2.1.3 Risk Analysis

Some form of risk analysis is used to determine the level of effort and investment in countermeasure design and installation in all countries visited. For example, Switzerland uses a matrix to code flood hazard zones into increasing degrees of hazard (i.e., yellow, blue, and red) and infrastructure design and maintenance decisions are guided by the degree of risk involved. The determination of protection objectives, and thus of the design flood discharge, is considered a decision of major technical and economic consequence. Formerly, in Switzerland, the design for protection works was generally based on a flood with a return period of 100 years (HQ_{100}). Today, a differentiation of protection objectives is applied (Figure 2). According to the importance or value of structures and land to be protected, the respective degree of safety can be chosen *(23)*. For example, for infrastructure of national importance complete protection would be provided up to a flood (Q_a) that represents the limit of damage (approximately a 50-year return period). Limited damage (but not failure) would be accepted up to a flood that represents the limit of danger (Q_b). Beyond that point, no protection would be provided in terms of structural or hydraulic design, but flood warning, evacuation, or bridge or roadway closure would be used to reduce the potential for loss of life.

As an example of the consideration of risk in design, in the Netherlands it is recognized that absolute safety against storm surges is nearly impossible to achieve in practice *(22)*. Therefore, the Dutch prefer to evaluate the probability of failure of a certain defense system. The ultimate potential threat for Dutch sea defenses is derived from extreme storm surge levels with a very low probability of exceedance (1 percent per century for sea-dikes) and equated with the average resistance of the dike. Under these ultimate load conditions, probability of failure of the dike (seawall) should not exceed 10 percent. To apply this method, all possible causes of failure have to be analyzed and the consequences determined.

In Europe, the fault tree is considered a useful tool for integrating the various failure mechanisms into a single approach *(8, 16, 22)*. For example, Figure 3 shows the fault tree for bed protection in which the foundation of the hydraulic structure is the central point *(8)*. The bed protection has to prevent or slow down a change in the geometry of the foundation. A failure of the bed protection does not directly imply the loss of the structure. However, when the subsoil becomes unstable because of the existence of a well-developed scour hole, the resistance of the foundation is reduced.

A further advantage of fault tree analysis is that this makes it possible to incorporate the failure of mechanical or electrical components as well as human errors in the management and maintenance of the structure. For instance, the safety of a sluice can be dramatically improved by regular echo-sounding of the bed protection and by subsequent maintenance if the initiation of a scour hole is discovered. The probability of instabilities affecting the foundation is

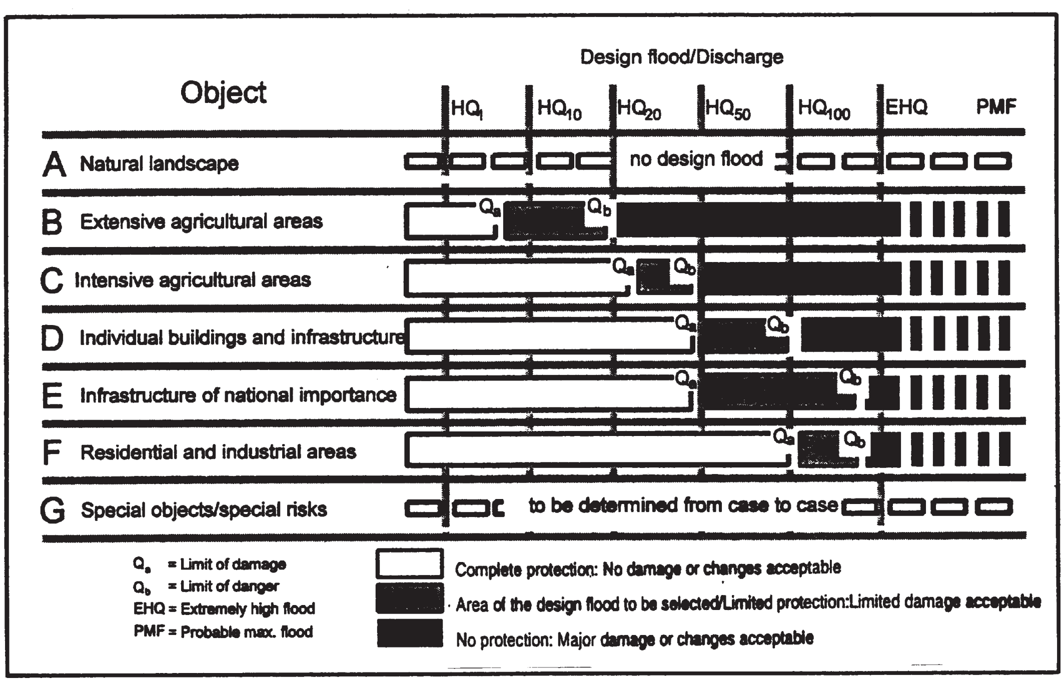

Figure 2. Differential safety concept—according to safety objectives a variable design flood can be applied for flood control works (23).

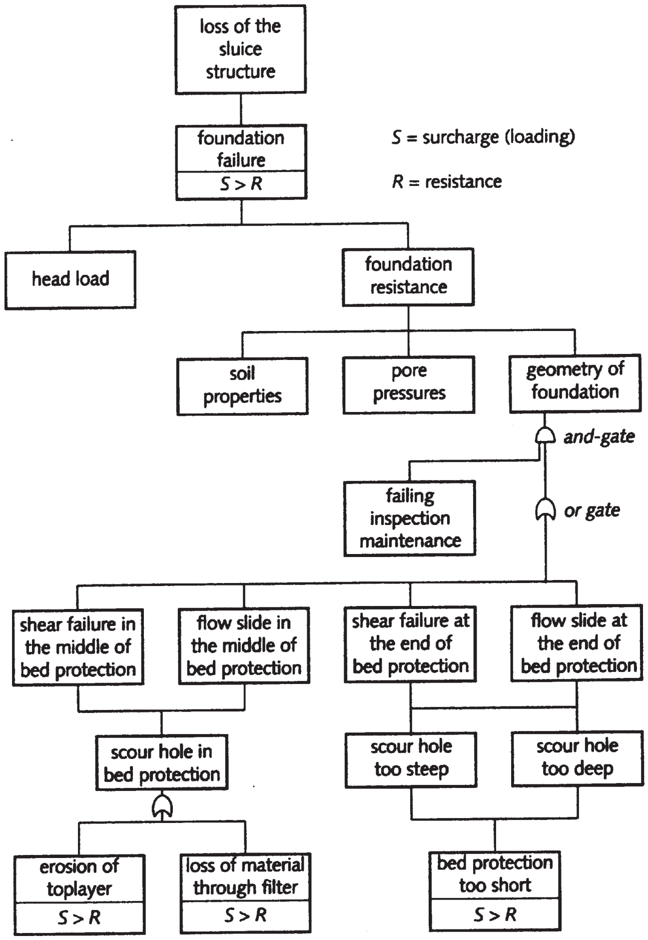

Figure 3. Fault tree for bed protection (8).

thus reduced to the coincidence of scour hole formation and failings in inspection and maintenance *(8)*.

More information about the design process, including outlines of main considerations relating to deterministic and probabilistic design processes used in Europe, can be found in *CUR Report #169 (17)*.

2.1.4 Environmental Policy

Environmental impacts are considered for scour and stream instability countermeasure selection, design and installation in all countries visited. In general, the approach is to emphasize environmental enhancement and sustainability, without creating an undue risk to lives and property in applying environmental policy to structures in a riverine system.

In the United Kingdom, for example, the Environment Agency is developing draft technical guidelines for erosion assessment and management in relation to waterway bank protection *(15)*. Selecting a strategy for controlling bank erosion depends on the following:

- Identifying the problem and its causes;
- Determining the principles and objectives of control for the specific site;
- Prioritizing those objectives;
- Assessing the risks associated with adoption of the strategy, depending on the likelihood and the consequences of failure; and
- Cost-effectiveness.

The strategies are classified into six types:

- Allowed natural adjustment,
- Management,
- Relocation,
- Bioengineering,
- Biotechnical engineering, and
- Structural engineering.

The strategy chosen should be the most cost-effective one that addresses the cause and severity of the problem in the most environmentally sensitive way.

In particular, the strategy should consider the consequences of bank failure. Where these are rated as severe, the risk associated with the failure of any strategy is high. A low-risk strategy is, therefore, appropriate. For example, where flood defense is in question or navigation threatened, structural engineering is likely to be the only appropriate strategy (Figure 4). Where the consequences of bank erosion are less significant, a riskier solution may be more appropriate because of its lower cost and, compared with structural engineering, its greater benefit to ecological habitat and landscape *(15)*.

The first three strategies are considered "Management Solutions," and guidance recommends that a management

Figure 4. Property close to a river bank limits the choice of strategies for erosion control. Structural solutions, such as gabions, are often the only feasible measure (15).

approach to dealing with bank erosion problems should always be the first option considered. Management solutions are preferred because they involve less interference with the natural environment and can often be justified in terms of environmental protection. Further, it is only by considering management options first and taking a positive decision to "rule them out" that a choice of any structural solution can be properly justified *(15)*.

A structural engineering strategy, sometimes termed "hard engineering," includes the use of steel, concrete, and timber piling. The approach also includes structures placed within the channel to control the flow. These include groynes (spurs), vanes, and weirs *(15)*.

Although structural engineering has the lowest risk of failure of the six strategies, it is suggested that it should not be used simply because this is the case. Structural engineering should be viewed as the "last resort," appropriate only where all other strategies have been purposely ruled out. It is however, likely to be the only effective strategy wherever the integrity of the entire channel is threatened. It is appropriate wherever there is a risk of the following:

- Flooding of surrounding land;
- Damage to structures;
- Damage to property, towpaths, roads, railways, and so forth; and
- Damage to canal lining with consequent loss of water in the channel through leakage.

Wherever structural engineering is chosen, it should be justified. The purpose of the strategy should be defined, and it should be clear why it is essential *(15)*.

The European approach to bioengineering and biotechnical engineering is discussed in a subsequent section.

2.1.5 River Geomorphology

In the United States, FHWA's HEC-20 *(3)* stresses the need to take a river system/geomorphic approach to channel instability problems. All four countries in Europe recognize the value of a geomorphic analysis in bridge and countermeasure design. At Delft Hydraulics, geomorphologists as well as experts on remote sensing are employed in river training studies. At the University of Nottingham in the United Kingdom, research in applying geomorphic reconnaissance techniques to river engineering problems has produced useful and practical guidance for the hydraulic engineer. Such techniques support geomorphic classification of a river system and permit a detailed investigation of form and process for critical reaches where instability could affect bridge design or countermeasure selection, design, and maintenance *(20, 21)*.

The *Stream Reconnaissance Handbook (20)* notes that the purpose of stream reconnaissance is as follows:

- To supply a methodological basis for field studies of channel form and process;
- To present a format for the collection of qualitative information and quantitative data on the fluvial system;
- To provide a vehicle for progressive morphological studies that start with a broadly focused catchment baseline study, continue through a fluvial audit of the channel system, and culminate with a detailed investigation of geomorphological forms and processes in critical reaches; and
- To supply the data and input information to support techniques of geomorphological classification, analysis, and prediction necessary to support sustainable river engineering, conservation and management.

A set of field record sheets (checklists) is presented in the *Handbook* to support a range of reconnaissance objectives, including the following: stream classification, an engineering-geomorphic analysis, field identification of channel stability near structures, and supplying input for stable channel design techniques and modeling of the river system.

In the United Kingdom, the Environment Agency, through the National Centre for Risk Analyses and Options Appraisal, has published a practical guide to river geomorphology *(19)*. The Guide notes that river geomorphology provides a practical basis for the assessment, protection, and enhancement of the physical environment in river channels. In this context, the Environment Agency can better achieve its objectives of protecting or enhancing the environment by adopting a geomorphological approach to river management. The geomorphological approach is also consistent with a holistic view of the environment, and the application of geomorphologically aligned design and management can contribute toward achieving sustainable development and avoiding committing future generations to inflexible solutions or expensive channel maintenance *(19)*.

On the basis of large-scale hydraulic modeling experiments, H.R. Wallingford in the United Kingdom has developed and published for the National Rivers Authority interim guidelines for design of straight and meandering compound channels. A hand calculation methodology is presented, and implications for 1-dimensional river modeling are discussed *(18)*.

2.1.6 Scour Prediction

Although investigating improved scour prediction techniques was not the primary purpose of the scanning review, methods to calculate scour, particularly in complex flow situations, were of interest to the scanning review team members. The problems of estimating scour at wide piers, the time rate of scour in cohesive and non-cohesive materials, and the interaction of the various scour components are recognized as being among the most pressing U.S. research needs in scour.

Scour prediction in Europe relies heavily on pioneering work by Breusers, Raudkivi, Shields, Laursen, Neill, and others. However, FHWA HEC-18, "Evaluating Scour at Bridges, *(2)* is referenced in both of the recent scour references developed in the United Kingdom *(9, 13)* and is evaluated in some detail in the Dutch *Scour Manual (8*, p. 115*)*.

The Dutch *Scour Manual (8)* provides the most comprehensive treatment of scour prediction of the European publications encountered during the scanning review. Standard practice for scour prediction in the United States will benefit from careful consideration of the material presented (which extends the general introduction given by Breusers and Raudkivi in 1991) *(24)*. The *Scour Manual* is viewed by its authors as a "revitalization" of Breusers' equilibrium method with the addition of laboratory and field experience gained in the Netherlands and abroad.

Several of the topics in the Dutch *Scour Manual (8)* that relate to high-priority research needs in the United States are discussed in more detail in Appendix D. These include time scale (characteristic time) for development of scour and scour at wide piers. For example, the Dutch divide the process of local scour around bridge piers into several phases: initial phase, development phase, stabilization phase, and equilibrium phase. A "characteristic time" is defined as the time it takes for scour to reach a depth equal to the pier width for pier scour or as the time for scour to reach the initial flow depth for more general scour situations (see Appendix D for potential applications in the United States).

At H.R. Wallingford in the United Kingdom, research is ongoing for scour prediction under reversing (tidal) flow conditions. Again, the definition of a characteristic time is considered important. The Dutch *Scour Manual (8)* also considers scour under unsteady (tidal) flow conditions and offers several methods for estimating scour depth.

For scour at wide piers, the approach in Europe is to determine the point at which the process makes the transition from scour on a "slender" pier (influenced largely by pier width) to scour on a wide pier (influenced primarily by water depth). Appendix D contains discussion from Delft Hydraulics on the wide pier problem.

The Dutch *Scour Manual (8*, pp. 19-22*)* presents a methodology to determine critical velocity in cohesive sediments but observes that "the erosion characteristics of cohesive sediments are not yet fully understood." At the H.R. Wallingford Laboratory, specialized apparatus has been developed to investigate the time rate of scour in cohesive materials.

In Europe, in general, the influence of turbulence in relation to the structure (e.g., bridge and storm surge barrier) is considered a key factor for estimating scour potential and designing scour countermeasures. Information on model testing, analysis, and design of bed protection for the Rotterdam storm surge barrier is presented by Jorissen et al. *(25)*.

In estimating scour at a bridge pier, researchers in the Netherlands consider the interaction between the various scour components (e.g., long-term degradation, general or contraction scour, and local scour) when calculating total scour. The interaction between scour holes on adjacent substructure elements is considered indeterminate. At Delft, research has been conducted on the combined effects of lateral channel migration and local scour, specifically the development of scour on groins in meander bends. The Dutch consider the most pressing research needs in scour prediction to be as follows:

- Prediction of bed levels during floods in relation to the general morphological behavior of the river,
- Determination of the relationship between the flood wave and the speed with which the riverbed responds (i.e., the relationship between scour development and flood duration), and
- Development of techniques to estimate the superposition of general and local scour (e.g., scour at a pier in a river bend or the interaction of contraction scour and local scour in a straight reach of river).

2.1.7 Modeling

Both physical hydraulic modeling in a laboratory and numerical computer modeling are among the standard techniques available to analyze the scour problem and design countermeasures. The scanning review team members visited hydraulic modeling laboratories with exceptional facilities and capabilities at the laboratory of Hydraulics, Hydrology, and Glaciology of the Swiss Federal Institute (VAW/ETH) in Zurich, Switzerland; the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe, Germany; and the H.R. Wallingford Laboratory in Wallingford, United Kingdom. At Delft Hydraulics it was pointed out that the laboratory had extensive experience abroad in bridge scour, stream stabilization, hydraulic studies, and, very often, physical modeling in a local laboratory is carried out in conjunction with studies of these subjects.

In Europe, it is much more likely that physical modeling, often in conjunction with computer modeling, will be an integral part of the hydraulic design process for bridge foundations and countermeasures than is typical in the United States.

A major effort is underway in Europe to develop 1-, 2-, and 3-dimensional computer models with hydrodynamic, sediment transport, and in some cases, morphologic capabilities. For example, Delft Hydraulics, an independent, non-profit-distributing institute (privatized since 1991) has established a goal to become a center of expertise in computer modeling. Delft also maintains extensive physical modeling capabilities for three reasons: validation of computer modeling, fundamental research with respect to physical processes, and solving problems for which computers cannot presently be applied.

The Danish Hydraulic Institute's (DHI) computer model MIKE 11, a dynamic, 1-dimensional modeling system for river and channels, is widely used in Europe and abroad. The U.S. Army Corps of Engineers HEC models are also used in Europe. However, each of the laboratories visited had proprietary computer models for river-related analyses and had programs underway to develop enhanced software capabilities.

At VAW in Switzerland, computer models and model development efforts included the following:

- MORMO (MORphological MOdel) a 1-dimensional quasi-steady-state model for simulating sediment transport in rivers and reservoirs;
- A 2-dimensional mobile-bed process model; and
- FEMTool (Finite Element Method Tool Box) for 1-, 2-, and 3-dimensional hydrodynamic problems, with a 2-dimensional mesh generator.

At BAW in Germany, 1-dimensional unsteady flow modeling was being used to evaluate river behavior and determine maintenance requirements. Data from both physical models and field monitoring were being used to refine and calibrate the model.

At Delft Hydraulics in the Netherlands the following software is being used or under development for river engineering analyses:

- RIVCOM: a 2-dimensional computation of bed level changes, including spiral flow effects;
- SERES: a computation of sedimentation in reservoirs;
- SUSTRA/SUTRENCH: a computation of morphological effects resulting from changes in sediment transport, dredged trenches, and so forth;
- MIANDRAS: a computation of river meanders;
- SOBEK-GRAD: a special 1-dimensional module for dynamic simulation of the morphology of graded riverbeds;
- DELFT2/3D-MOR: a special 2/3-dimensional module for dynamic simulation of the morphology of uniform sediment and graded riverbeds;
- SCOUR: local erosion at hydraulic structures;
- DIPRO: a check of riprap and block revetment stability subjected to flow and wave-induced forces caused by passing ships; and
- SEDIM: sediment transport and management in hydraulic structures.

As an example of the computational hydraulic software available in the United Kingdom, H.R. Wallingford has developed HYDROWORKS, an advanced hydraulic simulator for stormwater, sewage, and combined wastewater systems.

Although several specialized models being developed in Europe may be of interest, it appears that 1- and 2-dimensional hydrodynamic modeling capabilities to support scour predictions and countermeasures design in the United States are comparable with what is currently available in Europe.

2.1.8 Inspection and Monitoring

Most of the countries visited have initiated efforts to develop a bridge inspection or scour evaluation program comparable to the National Bridge Inspection Standards (NBIS) in the United States. In Germany, the Federal Highway Research Institute (BAST) is investigating the use of the FHWA PONTIS bridge management system.

In Switzerland, specific guidance on the stability of structures in water has recently been published (1998) as a multi-agency guideline by the Federal Office for Highways (ASTRA), the Federal Office for Transport (BAV), the Federal Office for Water Management (BWW), and the Swiss Federal Railways (SBB). This document is presented as a "Recommendation for the preservation and maintenance of existing structures/Hints for the construction of new structures." *(7)*. The guideline contains illustrations of typical forms of damages and processes (e.g., scour) endangering bridge structural components in water, procedures to assess the safety and stability of those structural components (including risk assessment), and inspection methods and techniques. A flow chart (Figure 5) guides the process.

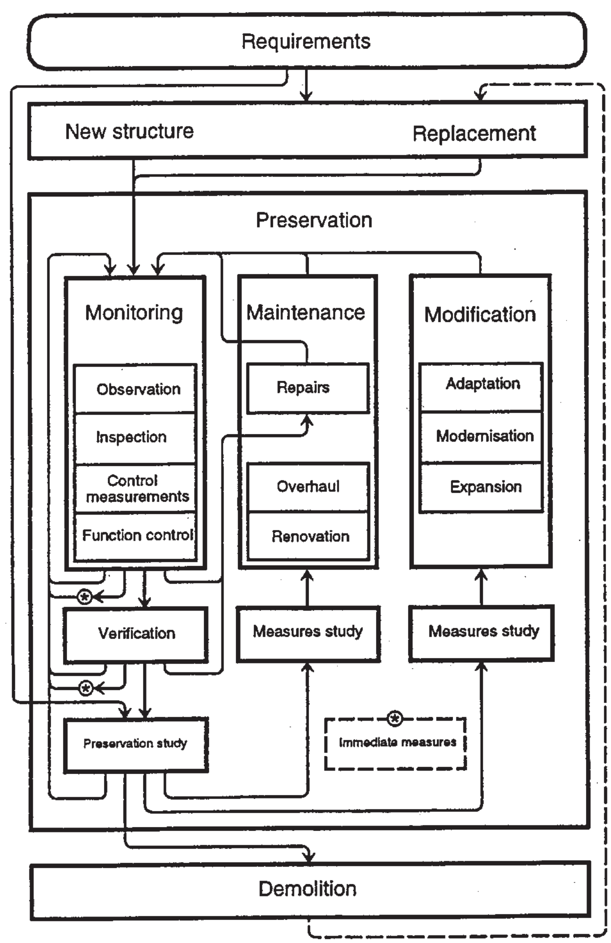

Figure 5 Flow chart for preservation of engineering structures in water (7).

In response to the Glanrhyd bridge failure in 1987, high water marks were painted on most railroad bridges in the United Kingdom to guide inspectors' decisions on caution or closure, but this approach apparently met with only mixed success as it resulted in unnecessary bridge closures. Railtrack Handbook 47 on scour was prepared to provide guidance on techniques to assess the failure risk to structures subjected to hydraulic loading and techniques to implement procedures to safeguard traffic and personnel under extreme flood conditions *(9)*. An initial assessment is prescribed following the procedures of Appendix B to the Handbook, which is a report by H.R. Wallingford on "Hydraulic Aspects of Bridges: Assessment of the Risk of Scour."

Specifically, Appendix B to Railtrack Handbook 47 presents advice and guidelines to enable British Rail to assess hydraulic aspects of bridges over water. Possible causes of failure are discussed and illustrated with a series of figures (Table 1). The Railtrack assessment method involves a prescriptive assessment procedure designed for use by non-specialist engineering staff. The method's purpose is to provide a preliminary scour risk assessment in order to identify those structures that require further in-depth study. The assessment involves the user in defining a potential flood depth. The calculation method then uses this information in combination with data gathered on site on the river channel, bridge dimensions and bed material, to estimate a potential scour depth. The scour depth is then compared with the foundation depth to derive a preliminary priority rating. Structures in the highest priority classes are recommended as requiring further detailed analysis to confirm the risk of undermining from scour *(9, 11)*.

For the Highways Agency in the United Kingdom, an Advice Note has been prepared to assist in the assessment and analysis of scour at highway bridges *(13)*. The methodology proposed in the Advice Note (Figure 6) comprises the following stages:

- An initial screening stage;
- A second stage in which an estimate is made of the potential depths of scour adjacent to the bridge based on a site visit and estimated 200-year flood flow; and
- A simple method of prioritizing those bridges that may be at some risk, as a function not only of the scour depths, but of several other relevant param including the importance of the bridge.

If the second stage identifies a bridge to be at some risk from scour, then further consideration of that bridge may be required, either in the form of more detailed studies and investigations with a view to carrying out such remedial works as may be required or the implementation of such works if the costs are such that direct implementation would

TABLE 1 Elements of a river crossing that may be subject to scour *(9)*

Bridge Element	Primary Risks	Main Worsening Features	Secondary Risks	Figure No.
Bridge pier in main river channel	• Local scour • General scour	• Angle of attack on elongated pier • Channel constriction • River bend at bridge immediately upstream • Shallow foundations	• Channel stability • Dredging • Changes to river or catchment • Floodplain constriction	1
Abutment projecting into main river channel	• Local scour • General scour	• Angle of attack • Channel constriction • Floodplain constriction • Abutment on outside of bend • Shallow foundations	• Channel shifting • Dredging • Changes to river or catchment	2
Bridge pier on floodplain near main river channel	• Channel shifting/bank instability • Local scour	• River unstable • Banks unstable/unprotected • Outside of bend • Shallow foundations	• General scour	3
Abutment on floodplain near main river channel	• Channel shifting/bank instability	• River unstable • Banks unstable/unprotected • Shallow foundations • Outside of bend	• Local scour • Erosion behind abutment	4
Bridge pier on floodplain set well back from main river channel	--	--	• Local scour	5
Abutment on floodplain set well back from main river channel	--	--	• Local scour • Erosion behind abutment	6
Flood relief arch	• General scour and 'culvert' flow	• Large constriction of floodplain • Deep floodplain flows	--	7
Earth embankment, e.g., approach embankment	• Erosion • Slope failure exacerbated by high pore-water pressure	• High-velocity floodplain flows • Large constriction of floodplain • Wave attack • Erodible embankment soil	--	8

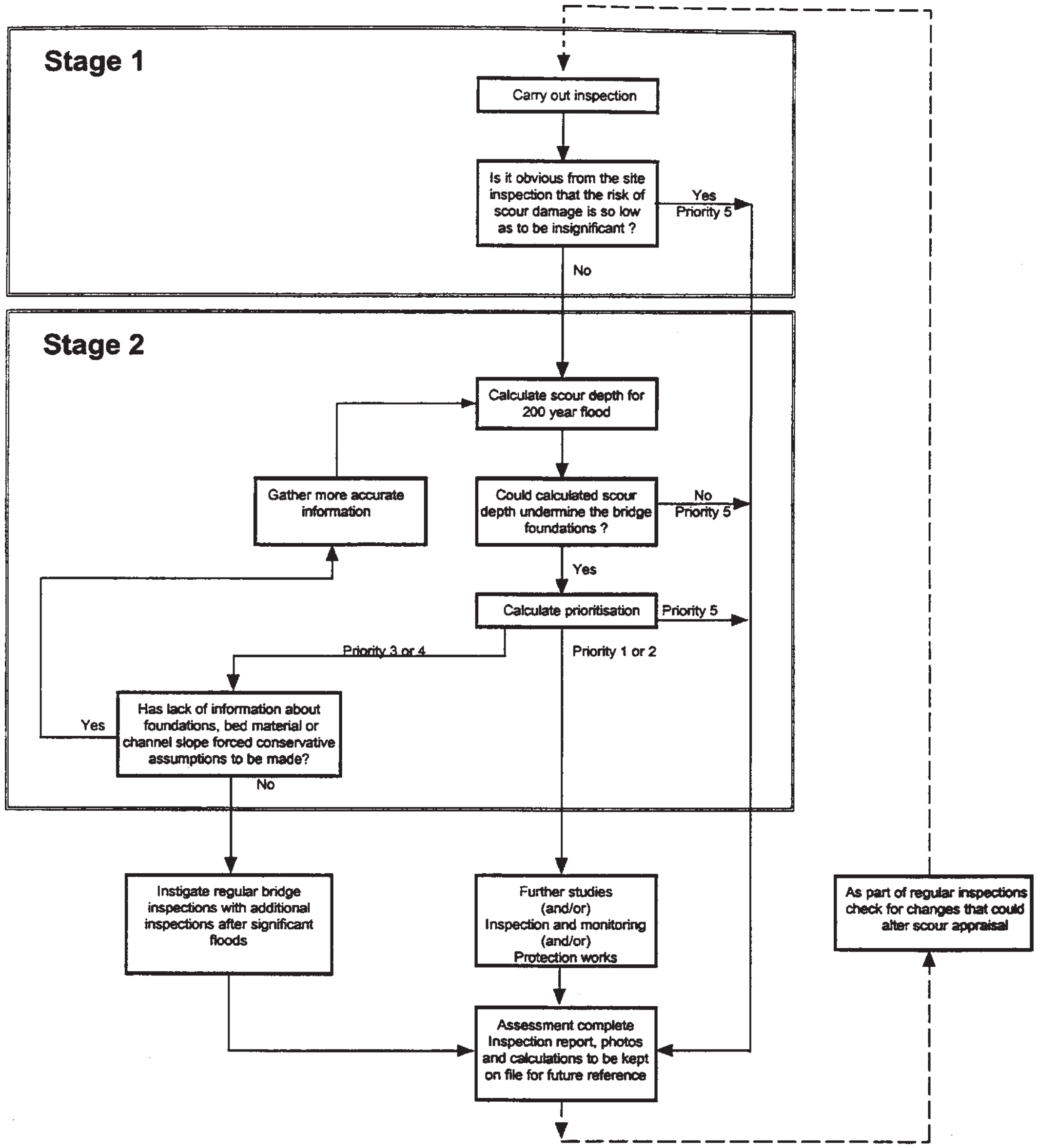

Figure 6. Overall scour assessment methodology (13).

be the cheapest option. The prioritization provides a means of identifying those bridges at which resources should first be concentrated. If further studies or works are considered necessary, then specialist advice is recommended *(13).*

Using 12 bridge sites in the field, a comparison of the British Railtrack and Highways Agency procedures was completed by Jeremy Benn and Associates *(11)* to identify any theoretical differences between the two methods and to check on consistency between the priority rating scales. Among the general conclusions was the observation that both the methods use scour theory from the United States to estimate scour depths. This approach is considered extremely conservative when used in United Kingdom practice because of the following *(11)*:

- "Many of the scour equations were derived from physical model tests using unconsolidated, non-cohesive sediments whereas many United Kingdom bridges lie on consolidated material. In particular, given that many United Kingdom bridges are more than 100 years old, the degree of consolidation of sediments beneath the bridge supports must be considerable (as this will enhance the scour-resisting properties of the material)."
- "United Kingdom flood frequency curves are generally less steep than those in less temperate climates such as the United States. In other words, the relative differences between a 100- and 200-year design flood are less than that in other countries and hence the sensitivity of priority rating to design flood is less marked."

An effort comparable to NCHRP Project 21-3 has been made in the United Kingdom to develop fixed instrumentation for measuring and monitoring scour at bridge piers and abutments. This resulted in the patented Wallingford "Tell-Tail" device which was installed on several railroad bridges following the Glanrhyd bridge failure.

In none of the four countries visited was technology available to determine the characteristics of unknown bridge foundations (i.e., foundations for which design or as-built drawings do not exist). In the United Kingdom, there are numerous unknown foundation bridges and the problem is considered as serious as it is in the United States.

2.2 OBSERVATIONS ON SPECIFIC COUNTERMEASURES

2.2.1 Riprap

The use of riprap (i.e., armor stone in combination with a geotextile or granular filter) is by far the most common scour and stream instability countermeasure in all countries visited in Europe. Its availability, economy, ease of installation, and flexibility are considered highly desirable characteristics in all four countries visited. As a result, considerable effort has been devoted to techniques for determining size, gradation, layer thickness and horizontal extent, filters, and placement techniques and equipment for revetment and coastal applications. In Europe, riprap is considered an effective and permanent countermeasure against channel instability and scour, including local scour at bridge piers.

Generally, riprap is sized using the Hudson formula (coastal applications), Shields diagram, or methods developed in New Zealand, the Netherlands, the United Kingdom, or the United States. The need for designing the riprap for a specific site was emphasized. Great care is taken in placing the riprap at critical locations, and, in many cases, stones are placed individually in the riprap matrix. Highly specialized equipment has been developed by construction contractors in Europe for placing riprap, particularly for coastal installations. The use of bottom-dump or side-dump pontoons (barges) is common in both Germany and the Netherlands. By loading pontoon "bins" selectively with different sizes of rock, a design gradation in the riprap can be achieved. For large installations, vessels for placing riprap are equipped with dynamic positioning systems using Differential Global Positioning System technology and thrusters to maintain position and echo sounders (or divers) to verify the coverage of the riprap layer. Some of the smaller pontoon systems, particularly the bottom-dump pontoons developed in Germany, could be used to place riprap in water at larger bridges.

The scanning review team members' visit to the Eastern Scheldt Barrier in the Netherlands provided an introduction to riprap design techniques and specialized construction (placement) capabilities used in Europe. Following the catastrophic floods of 1953, which inundated large areas of the Delta (Figure 7) and claimed 1,853 lives, the Delta project was undertaken to close the main tidal estuaries and inlets in the southwestern part of the Netherlands, except for those giving access to the ports of Rotterdam and Antwerp. The Eastern Scheldt Barrier (Figure 8) was the final part of the project (completed in 1986) and consisted of a series of 18,000-ton concrete piers creating a dam with moveable gates.

To increase the stability of the piers once they were installed, a sill built up of graded layers of stone was constructed under water around the base of the piers. The outer layer of 6- to 10-ton stone was designed to withstand currents expected should one of the gates not close during a storm. The largest stones could not be dropped into position, as the risk of their damaging the piers was too great. A specialized vessel, the Trias, was designed to lay the top layer of stone. This vessel was equipped with a large crane with a long extendible arm that was used to place the heavy stones accurately. Five million tons of stone were used in the construction of the sill. Figure 9 shows the stone deposition barge, a stone dumping pontoon, and a schematic of the placement process *(26)*.

At the BAW in Germany, the scanning review team members observed wave tank testing of prototype scale partially grouted riprap (Figure 10). In general, the objective is to increase the stability of the riprap without sacrificing all of the flexibility. Contractors in Germany have developed

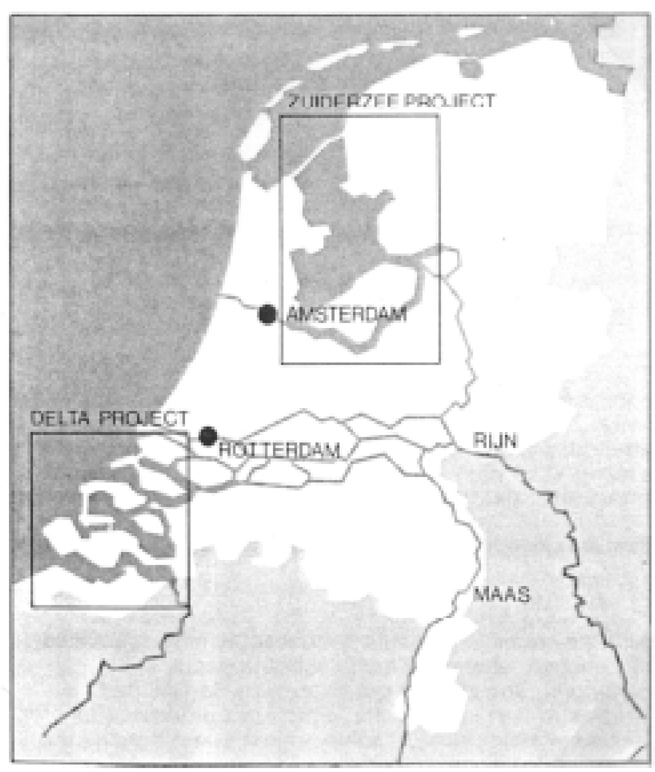

Figure 7. Map of the Netherlands and the Delta Project (26).

Figure 8. The Eastern Scheldt Barrier, the Netherlands.

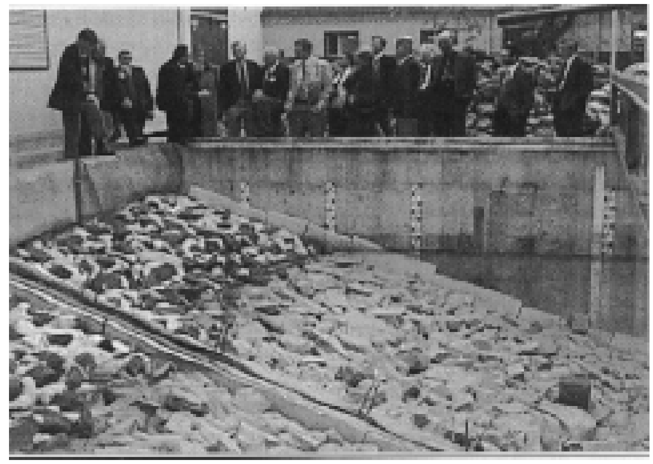

Figure 10. Wave tank test of partially grouted riprap—BAW, Karlsruhe, Germany.

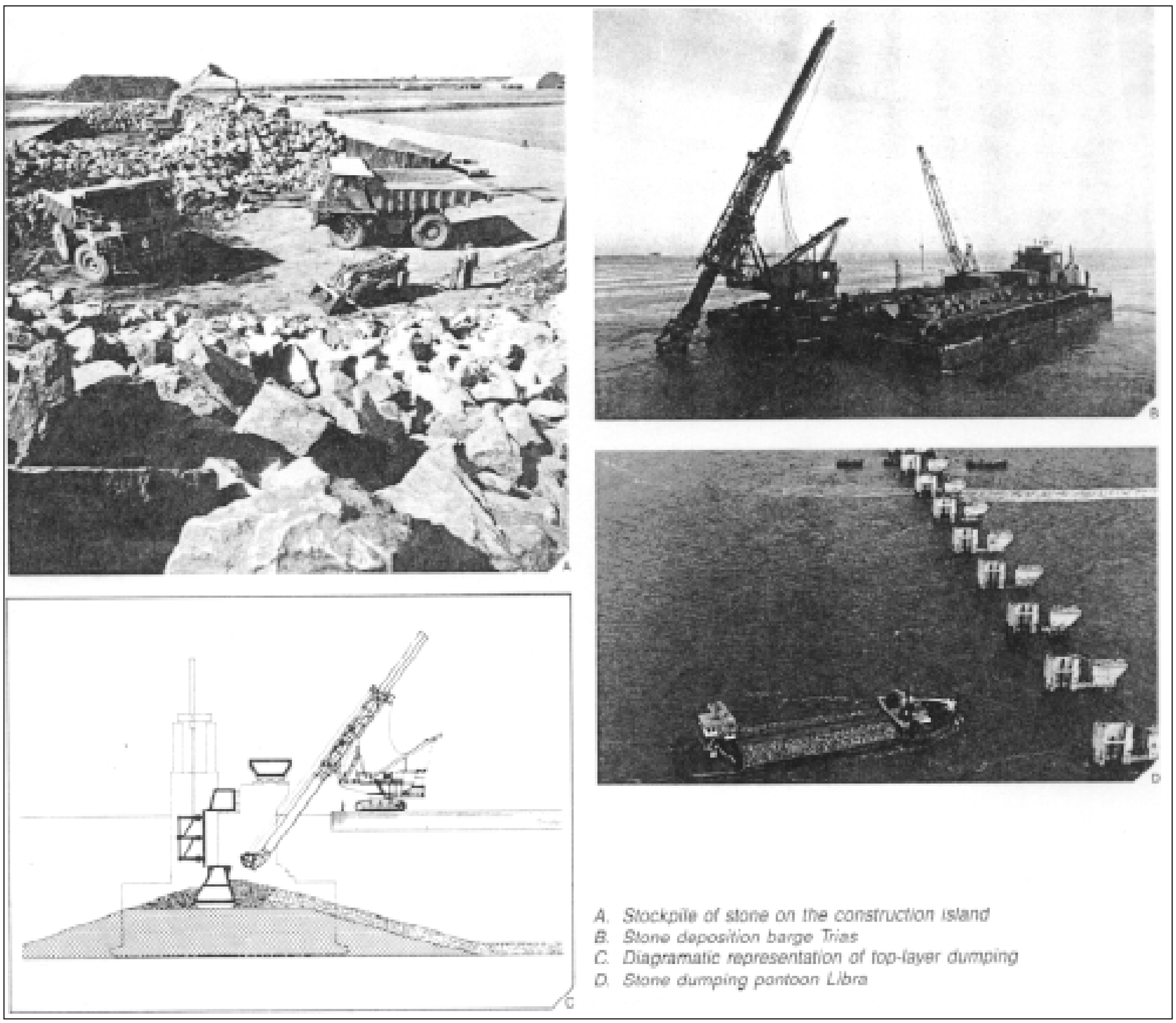

Figure 9. Armor stone and specialized stone placing equipment—Eastern Scheldt Barrier, the Netherlands (26).

techniques and equipment to achieve the desired grout coverage (i.e., filling about 40 percent of the voids at the surface) and the right penetration (i.e., decreasing grout fill with depth into the riprap matrix and no grout in contact with the geotextile filter). With the correct slurry mix (recipe) partial grouting can be achieved underwater with minimal environmental impact. Although current guidance in the United States tends to discourage the use of grouted riprap, BAW engineers believe that partial grouting, if done correctly, will ensure that the riprap retains sufficient flexibility while enhancing stability. Partial grouting of riprap may be well suited for areas where rock of sufficient size is not available to construct a loose riprap revetment. Partial grouting of riprap is presented as one of several standard design forms for permeable revetments in a discussion of considerations regarding the experience and design of German inland waterways *(27)*.

The river and channel revetments design manual recently published by H.R. Wallingford in the United Kingdom *(14)* provides design guidance for grouting "hand-pitched stone" with both bituminous and cement grout. For grouting riprap in the United Kingdom, bitumen is the material most commonly used. Although various degrees of grouting are possible, effective solutions are usually produced when the bituminous mortar envelopes the loose stone and leaves relatively large voids between rock particles. The degrees of grouting available are as follows:

- Surface grouting (which does not penetrate the whole thickness of the revetment and corresponds to about one-third of the voids filled),
- Various forms of pattern grouting (where only some of the surface area of the revetment is filled, between 50 to 80 percent of voids), and
- Full grouting (an impermeable type of revetment).

Cement mortar is also used in conjunction with riprap, particularly to increase its stability at transitions with hydraulic structures or other types of revetment and is usually confined to small areas. Hand-pitched stone is normally grouted with cement mortar where it is necessary to provide increased stability, such as near the confluence of streams or at inlet or outlet structures. The workability of the mortar generally needs to be increased by appropriate additives *(14)*.

2.2.2 Filters

In Europe, as in the United States, a properly designed geotextile or granular filter is considered essential to the success of riprap and most other countermeasures on sand or fine-grained material. In Germany and the Netherlands, a significant investment has been made in the development and testing of geosynthetic materials, and innovative installation techniques have been developed that could find application for bridge pier and abutment countermeasures in the United States.

At the BAW in Karlsruhe, Germany, a highly specialized laboratory is available for testing a wide range of geotextile characteristics, including the following (1) impact testing performed to determine punching resistance (e.g., when large stone is dropped on the geotextile (Figure 11); (2) abrasion test (Figure 12); (3) permeability, clay clogging, and sand clogging tests; and (4) tests of material characteristics such as elongation and strength. Testing apparatus has been devised to test performance under typical conditions that might lead to failure when geotextiles are used with scour countermeasures. The scanning review team members are not aware of any similar test facilities in the United States. Through this testing program, geotextile materials have been developed for use in innovative approaches to filter placement for riprap and other countermeasures.

Geotextile containers (large sand bags) made of mechanically bonded non-woven fabrics up to 1.25 cubic m in volume have been used to provide a filter layer for riprap installation at several large projects in Germany. The containers are sewn on three sides at a factory and filled on site to approximately 80 percent of capacity with sand/gravel filter material using a hopper system. The final seam is sewn on site. The containers are placed in layers using a side-dump pontoon. The elongation capabilities of the fabric and partial filling allow the containers to adjust to irregularities of the substrate at the installation site. Riprap is then placed over the layer of geotextile containers *(28)*.

At the Eidersperrwerk storm surge barrier on the Eider estuary in Germany, a filter layer of more than 48,000 geotextile containers was used to repair a 30-m-deep scour hole at the barrier (Figure 13). An armor layer of 1- to 6-ton stone and toe stabilization using a fascine mat with smaller stone completed the installation. Similarly, a geotextile bag filter and riprap protection were used as a countermeasure against pier scour at a new bridge on the Peena River in Germany. The Dutch used a similar concept to place a filter at the Eastern Scheldt storm surge barrier (Figures 7 and 8). Instead of individual sand bags, large sand mats or mat-

Figure 11. Impact test apparatus—BAW, Karlsruhe, Germany.

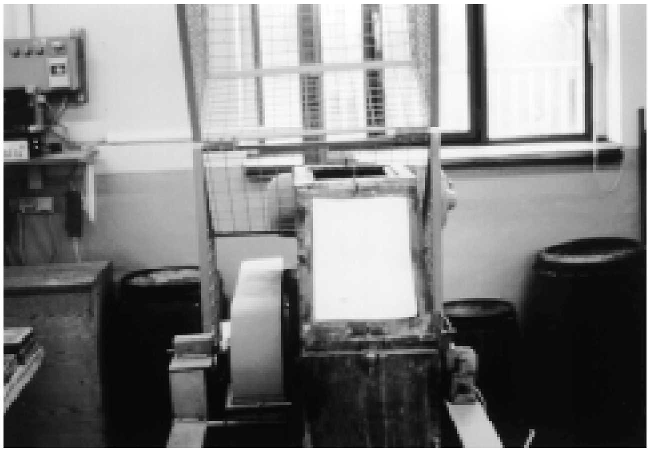

Figure 12. Abrasion test apparatus—BAW, Karlsruhe, Germany.

tresses (consisting of two layers of non-woven geotextile with granular material in between) were fabricated on land and placed with large barge-mounted rollers as a foundation for individual precast dam components and as a filter for riprap placed for scour protection *(26)*.

The Dutch have investigated the use of granular filters with large ratios for top layer and filter/base material instead of geometric tightness. Design rules for these "hydrodynamically sandtight" filters or geometrically open filters are presented by Bakker et al. *(29)*. The concept can be applied to geotextile filters and design rules for hydrodynamically sandtight geotextiles were developed at Delft Hydraulics. Erosion control by hydrodynamically sandtight geotextiles is discussed by Klein and Verheij *(30)*.

Three countries (i.e., Germany, the Netherlands, and the United Kingdom) use fascine mats, a very old, traditional approach for scour protection, as a means of placing a geotextile filter in deep water. The fascines consist of a matrix of willow or other natural material woven in long bundles (15 to 20 cm in diameter) to form a matrix which is assembled over a layer of woven geotextile. The geotextile has ties which permit fastening it to the fascine mat. The fascine mattress or "sinker mat" is floated into position and sunk into place by dropping riprap-size stone on it from a barge. Fascine sinker mats and riprap have been used to protect the toe of the geotextile container/riprap protection at the Eider estuary storm surge barrier in Germany (Figure 13) and for coastal applications in the Netherlands. Figure 14 shows a scanning review team member investigating the characteristics of a fascine mat at the New Waterway storm surge barrier near Rotterdam, the Netherlands.

The BAW Code of Practice for the use of geotextile filters on waterways *(31)* covers various filter applications. Other relevant publications are DVWK Guideline 306 *(32)* for Application of Geotextiles in Hydraulic Engineering and several Permanent International Association of Navigation Congresses (PIANC) guidelines *(33, 34)*. Many of the techniques referenced in this section are summarized in a 1996 paper by BAW staff on installation of geosynthetics in waterways *(35)*. Additional discussion is presented by Pilarczyk *(16)* and Kohlhase *(36)*.

2.2.3 River Training

River training and stabilization techniques against lateral channel migration in the major navigable waterways of Europe are similar to those employed by the U.S. Army Corps of Engineers on navigable waterways in the United States (e.g., the Mississippi, Ohio, and Missouri river systems). Groins and jetties projecting roughly perpendicular

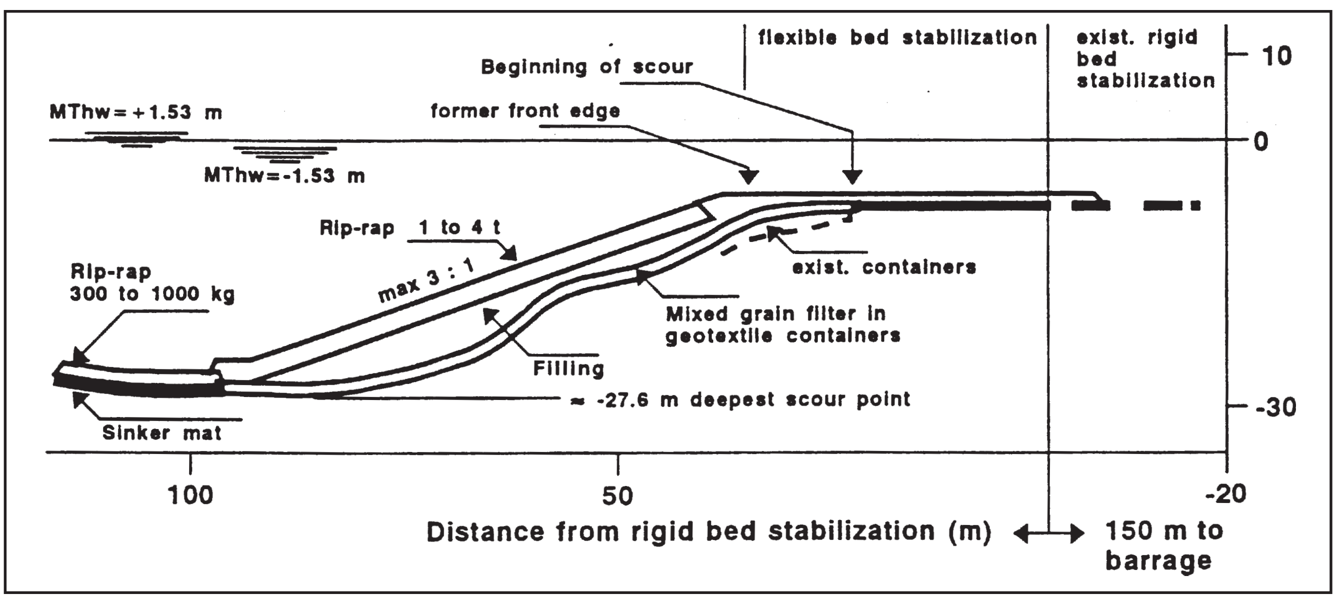

Figure 13. Eidersperrwerk on the Eiden estuary, Germany. Geotextile containers used to repair 3-m-deep scour hole and fascine sinker mat to stabilize the toe (28).

Figure 14. Fascine mat at new waterway storm surge barrier near Rotterdam, the Netherlands (Scanning review team member: Mr. Jorge Pagan—FHWA).

to the river bank, dikes placed parallel to the river bank, or revetment placed on the river bank are the most common river training works in Europe. Generally, riprap is the preferred construction material. Scour at the noses of groins and jetties, at the heads of dikes, and at the toes of revetments are the most commonly cited problems.

River training has been an ongoing process on Europe's navigable rivers (or on canals in the Netherlands) for hundreds of years, and there are few unprotected reaches of river. Thus, lateral instability because of river meander is a rare occurrence and is not considered a threat to bridges. On the Rhine River, from Koblenz to Mainz (the only reach of river that scanning review team members were able to observe in detail [Figure 15]), long parallel dikes (placed roughly one third of the channel width from the river bank used to constrict the flow) are much more common than in the United States, where a groin field would be used for the same purpose. Flow is allowed to pass through the area between the dike and the river's bank, sometimes over a submerged groin or weir (Figure 16).

To protect the toe of river bank (or canal bank) revetment, two approaches are usually employed. Either a toe trench is excavated and riprap is placed in the trench, or a "falling apron" approach is used. The falling apron or self-launching of riprap revetment was mentioned in all four countries. With this approach, stone is placed in a windrow along a bankline or at the toe to be protected, and, as the river erodes into the bankline or toe, it launches the material along the face of the slope and onto the toe. Methods are available to estimate the amount of extra material required to protect the revetment toe and to compensate for not having a filter. A range of toe protection alternatives is illustrated in the H.R. Wallingford river and channel revetment design manual from the United Kingdom (Figure 17).

2.2.4 Riverbed Degradation

Sills, grade control structures, low check dams, or weirs constructed of various materials are commonly used in Europe to protect against vertical channel instability (degradation) as they are in the United States. However, innovative approaches to the problem that justify further consideration were presented in Switzerland and Germany.

In Switzerland, an experiment was undertaken in the field with local channel widening in lieu of replacing deteriorating check dams as a means of grade control on the Emme River near Berne *(23, 37)*. Enhanced environmental diversity on a narrowly channelized river is seen as a benefit, but some local instability and the need to protect the shoulders of the widened section may be a detriment.

In Germany, the approach to the problem of degradation on the Rhine River has involved sediment management on a large scale. Here, it is recognized that long-term degradation problems are generally related to a deficiency in the supply of sediment to a river reach or river system. As a result, a systemwide sediment management program has

Figure 15. Rhine River bank protection near Schloss Stolzenfels, Germany—revetment wall with riprap toe.

Figure 16. Low rock groin on the Rhine River, Germany.

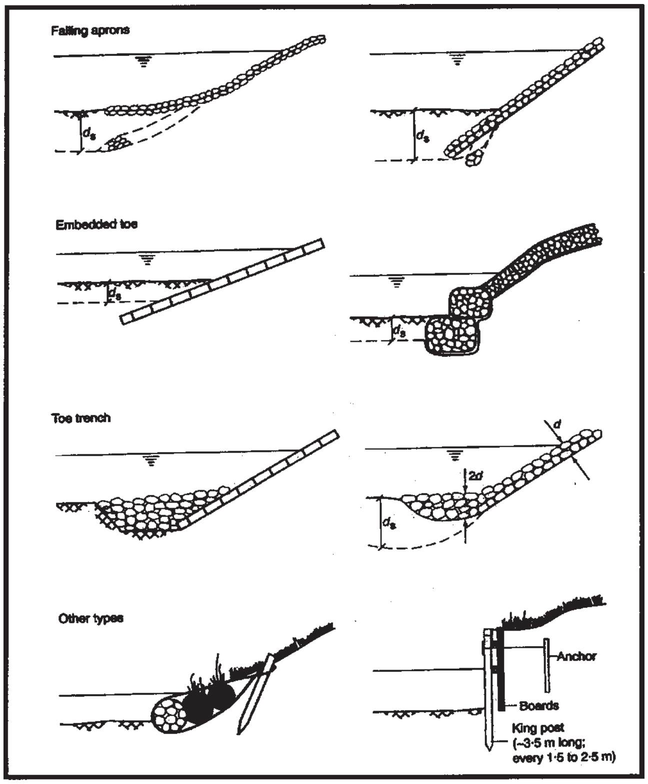

Figure 17. Examples of toe details (d_s is anticipated scour depth) (14).

evolved—one component of which is an attempt to replenish the sediment supply by "feeding the Rhine."

In the Rhine, the natural supply of bed-load material from the upriver reaches has been totally stopped by the impoundment system in the headwaters down to the Iffezheim dam at kilom 334 *(38)*. In order to avoid the formation of an "erosion wedge," an artificial supply of material has been provided down river through the dumping of gravel and sand from barges.

Between the last impoundment at Iffezheim and the German-Dutch border, research and field measurements have established the bed-load transport balance and identified nine river reaches with alternating aggradation or degradation regimes. In this reach of the Rhine, a sediment deficit of about 350,000 tons per year has been identified, and some 260,000 tons per year of "artificial" bed material has been supplied since 1991. This material has been derived from off-river sources and techniques such as dredging a transverse trench in the Rhine River bottom in an aggradational reach to trap sediment and transporting the material by barge to a sediment deficient reach *(39)*.

The Swiss also are concerned with the effects of sediment deficiency on river system stability. Before 1970, gravel mining (or harvesting) from rivers was allowed in Switzerland, but when scour problems were noted in adjacent reaches, the practice was restricted.

2.2.5 Alternative Countermeasures

Among the areas of particular interest to the scanning review team members during the scanning review were alternative countermeasures such as flow-altering devices or alternatives to riprap (particularly for the pier scour problem). The following paragraphs outline some of the scanning review team members' observations on alternative countermeasures in relation to U.S. practice.

Precast Armor Units

The floods of August 24-25, 1987, caused considerable damage in the Reuss River valley near Wassen, in the Canton of Uri, Switzerland. For example, the Swiss experienced a near catastrophic failure of a major national highway bridge when the Reuss River migrated laterally and undermined the foundation of a bridge pier (Figures 18 and 19). The countermeasure system developed by the VAW/ETH laboratory included a pile wall in front of the bridge piers, five concrete spurs, large concrete groins, and the placement of about 175 concrete prisms to correct and prevent further channel migration or lateral erosion.

The riverbank between the groins was protected by the precast concrete prisms, triangular in cross section, placed individually as revetment. In lieu of smaller interlocking armor units that would be costly to fabricate, the decision was made to cast much larger prisms with a simple shape and use the mass of the prisms to protect against river bank scour. The precast, hollow prisms were filled with concrete after they were placed in their final position. The groin field and prism revetment were then covered with a layer of natural stone for aesthetic and environmental reasons. The economics of the tradeoffs between smaller, high cost interlocking shapes for artificial riprap and simpler shapes with more mass are worth further consideration.

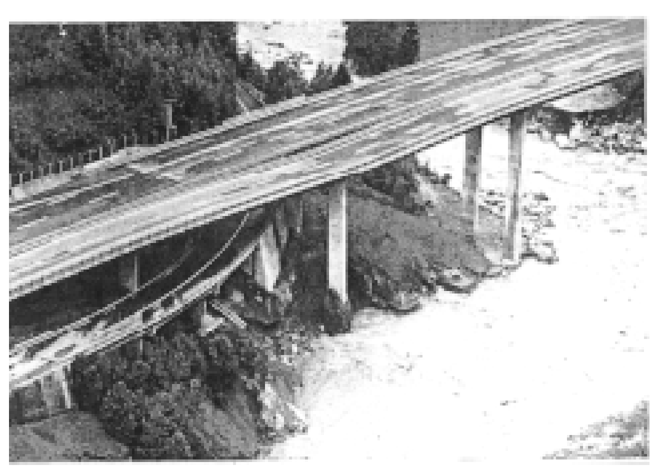

Figure 18. Reuss River bridge failure near Wassen, Uri Canton, Switzerland, August 1987.

Figure 19. Close-up of Reuss River bridge, Switzerland, August 1987.

Proprietary Products

In general, proprietary products such as interlocking block, articulating cable-tied block, and articulating grout-filled mattresses for revetment and channel bed protection are not considered as effective as riprap in Europe. The need for adequate toe protection and anchoring was emphasized. Block and mattress manufacturers in the United States and Europe are developing design criteria based on full-scale laboratory testing of specific products. Such tests should provide the necessary guidance for the successful design and installation of proprietary products for revetment and channel protection.

Recent laboratory testing by NCHRP, FHWA, and others in the United States indicates that when articulating mat products are used as a pier scour countermeasure, the joint between the mattress and the pier must be protected to prevent scour under the mat. The scanning review team members encountered two approaches to solving this problem that justify further evaluation. In Germany, reference was made (Dr. S. Kohlhase, University of Rostock) to a proprietary system for installing a collar and tying the geotextile filter underlying a mattress to the bridge pier using a pneumatic tie (Figure 20). This approach appears feasible for circular piers. Considering possible settlement of the mattress relative to the structure (pile), a steel sleeve and a "top hat" of filter fabric were proposed with a collar of fabriform laid on top of the mattress and tight to the sleeve as indicated in Figure 20. As relative settlement occurs, the sleeve is expected to slide down the pile and the top hat to expand, bellow fashion, with a collar for protection. This approach may be limited in areas where the top hat could be damaged by abrasion.

In the Netherlands, the recommended approach to the problem of sealing the joint between a mattress and a bridge pier is to place granular filter material to a depth of about 1 m below the streambed for about 5 m around the pier. The geotextile filter and block mat placed on the streambed over-

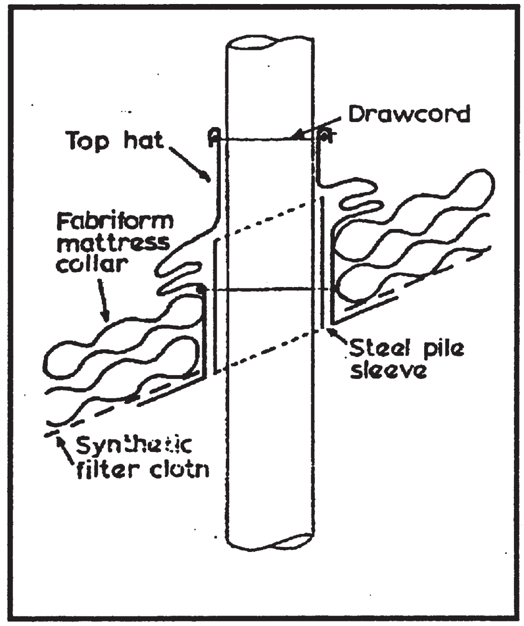

Figure 20. Flexible collar arrangement at a pile to seal the joint with a mattress.

lap this granular filter layer and the remaining gap between the mat and the pier is filled with riprap. Successful field installations have apparently been made using this technique.

Flow-Altering Devices

There is considerable interest in developing flow-altering devices such as hydrofoils, collars, and other bridge pier appurtenances as local scour countermeasures. Recent laboratory tests in the United States sponsored by NCHRP have shown that several of these types of devices, scour collars, sacrificial piles, and guide vanes, are only marginally effective. The scanning review team members did not encounter any successful applications of flow-altering devices as a pier scour countermeasure in any of the countries visited. However, researchers at the VAW hydraulic laboratory in Switzerland studied pressure flow at a bridge using devices to modify the flow. Pressure flow occurs when flood waters are high enough to submerge bridge superstructure elements or overtop the bridge deck. One of the devices studied was a curved plate, called a pressure flow shield, that is placed on the upstream side of a bridge *(40)*. The study concluded that the pressure flow shield could prevent overtopping and improve flow conditions through the bridge opening by scouring accumulated sediment from beneath the bridge. In another experiment at VAW the upstream, bottom edge of each bridge girder was modified by the addition of a rounded "nose." This improved flow conditions through the bridge under pressure flow and reduced backwater upstream of the bridge. This approach also appeared to decrease scour under the bridge and improve the passage of debris (trees and other vegetation) through the bridge opening.

Debris

Protecting bridges from the accumulation of debris and predicting the increase in scour caused by debris at a bridge is a problem worldwide. The scanning review team members did not encounter any applications of "debris deflectors" or other devices at a bridge during the scanning review. The Swiss were, however, experimenting with the design of large "trash racks" at sedimentation basins to catch vegetative debris before it moves downstream to a bridge. At the University of Nottingham in the United Kingdom, an effort has been made to develop software to aid in the prediction of scour when debris accumulate at a bridge.

2.2.6 Bioengineering

Bioengineering techniques are integrated with traditional engineering countermeasures for river system management in Europe; however, hydraulic engineers in all four countries visited do not recommend relying on bioengineering countermeasures as the only countermeasure technique if damage to property or to a structure or loss of life are possible. The primary concern expressed was a lack of knowledge about the properties of the materials being used in relation to force and stress generated by flowing water and the difficulties in obtaining consistent performance from countermeasures relying on living materials.

As discussed in the section on Environmental Policy, bioengineering and biotechnical engineering approaches are among the strategies considered when selecting techniques for controlling bankline erosion in the United Kingdom *(15)*. Accepted definitions of these terms are as follows *(14)*:

- Bioengineering—corresponding to the traditionally termed "soft revetments" using living plant materials, or plant products, as the primary means of protection;
- Biotechnical revetments—those revetments that incorporate some form of vegetative protection but also rely on the technical ability of harder materials (typical examples are grassed concrete blocks); and
- Structural revetments—revetments formed exclusively by non-live materials (examples include concrete lining and riprap).

Bioengineering is considered a suitable strategy in the United Kingdom under the following circumstances *(15)*:

- Conditions for the growth of vegetation species with engineering value are not limiting.
- Vegetation alone is able to protect the bank against scour (i.e., the flow velocity in the channel is less than the maximum "safe velocity" for the vegetation-lined channel).
- Plant roots can develop below the depth of any potential slide plane and thereby anchor the bank material to the underlying substrate.
- A long-term monitoring program can be designed and implemented.

The objective of biotechnical engineering in the United Kingdom is to combine the advantages of engineering structures with the engineering and environmental benefits of vegetation. In one view, the strategy combines the greater certainty associated with the design and performance of engineering materials with the uncertainty of the vegetation cover, providing a "back-up" should the vegetation, for any reason, fail. An alternative view is that it adds the greater resilience and indefinite life span of the vegetation cover to an engineering structure, resulting in an increase in the overall factor of safety *(15)*.

A PIANC document, "From Sheet Piling to Vegetated Embankments—Conventional and Biological Engineering Works for Bank Protection On Waterways" *(41)*, also appears representative of the general European approach to bioengineering and biotechnical engineering from a hydraulic engineering perspective. Here, a range of construction techniques—from traditional engineering to bioengineering—is reviewed. It is recognized that a correct approach is "to keep interference with nature as low as possible," and "in the field of hydraulic engineering there are many opportunities" to promote a natural balance (e.g., "by choosing natural construction materials and by suitable designs").

Several well-tested biological methods for bank protection have been used in Europe including the following: fascines, brushwood set in horizontal strips, brush layers/hedges, brushwood mats, vegetation mats, and wattle. The PIANC report *(41)* concludes that "if designed, planned and implemented properly, biological engineering works can meet both technical and ecological requirements." However, safety issues must generally be assessed by "purely technical aspects" and certain fundamental hydraulic and geotechnical requirements "have to be accepted as guidelines for river engineering and for the construction of safe waterways."

CHAPTER 3

APPLICATIONS TO U.S. PRACTICE

The scanning review team members were able to visit four European countries where they observed scour prediction techniques, inspection and monitoring practices, and numerous specific countermeasures for bridge scour and stream instability problems. Team members also were able to discuss design philosophy as well as these techniques, practices, and specific countermeasures with their European counterparts. The following sections (which summarize what the team members learned) discuss how European bridge scour techniques could be used to improve U.S. practice. These techniques should be considered further by appropriate research funding agencies (e.g., TRB, NCHRP, FHWA, and state DOTs and other bridge owners) or agen-

cies, such as FHWA and AASHTO, that establish transportation policy, code, guidelines, and specifications.

3.1 TECHNIQUES TO REDUCE BRIDGE SCOUR AND TO ENHANCE STREAM STABILITY

- Conduct a thorough review of European literature on bridge scour and stream instability technology, particularly the comprehensive scour manuals obtained during the scanning review. The references in Appendix C, available in English, provide a starting point, but numerous potentially useful references, not necessarily in English, remain to be identified and reviewed. The scope and potential value of the literature identified during the scanning review underscores the need to increase communications between researchers and practitioners in the United States and overseas.
- Re-evaluate bridge scour design philosophy regarding the role of countermeasures in new bridge design and construction. Consider techniques to move scour away from the structure during initial design and construction of bridges.
- Encourage increased use of risk analysis in the design of new bridges and evaluation of existing bridges. Consider accepting a variable degree of protection depending on the importance of the structure. Suggestions for applying risk analysis techniques to the bridge failure problem are discussed by Annandale *(42)*.
- Adapt stream reconnaissance techniques to the evaluation of stream stability in the vicinity of highway structures, and continue to encourage a geomorphic approach for stream system analysis, bridge design, and countermeasure selection.
- Improve techniques to analyze and predict scour, particularly for complex flow situations such as wide piers (see Appendix D), pressure flow, debris, and the interaction of general and local scour components by a more detailed evaluation of European practice.
- Investigate the role of turbulence intensity and its influence on scour prediction and countermeasure location and design.
- Investigate the characteristics of time rate of scour in non-cohesive and cohesive materials (see Appendix D).
- Increase the use of physical hydraulic models and computer models to evaluate scour in complex flow situations and for the design of countermeasures.
- Consider the applicability of sediment management as a strategy to counteract long-term riverbed degradation problems.

3.2 COUNTERMEASURE TECHNIQUES FOR BRIDGE FOUNDATIONS

- Evaluate fault tree analysis techniques for the selection and design of bridge scour and stream instability countermeasures. Suggestions for adapting fault tree analysis to analysis of a bridge failure resulting from scour and channel instability are provided by Johnson *(43)*.
- Review European inspection and monitoring programs and manuals in relation to the National Bridge Inspection Standards (NBIS).
- Evaluate the economics of including scour and stream instability countermeasures in the initial construction of a bridge.
- Evaluate the use of risk analysis in countermeasure design, particularly in the selection and design of countermeasures for existing scour-critical or unknown foundation bridges to ensure that the cost of the recommended solution is commensurate with the risk to the structure.
- Apply geomorphic reconnaissance and analysis techniques in the selection and design of countermeasures.
- Re-evaluate design and installation techniques for riprap and reconsider its viability as a permanent countermeasure against pier scour.
- Evaluate and test European techniques for the design and installation of partially grouted riprap and re-evaluate its applicability to U.S. practice.
- Evaluate and test the use of innovative techniques for placing filters under riprap and other countermeasures, including geotextile containers, geotextile mattresses, the use of fascine mats, and hydrodynamically sand tight filters.
- Investigate the economics of tradeoffs between smaller, high-cost interlocking shapes for artificial riprap (e.g., Toskanes) and simpler shapes with more mass to resist hydraulic stress (e.g., precast concrete prisms).
- Consider the relative merits of proprietary products (e.g., interlocking block, cable-tied block, articulating block, and mattresses) in relation to the use of riprap for channel protection and as local scour countermeasures, and encourage field and laboratory testing of these products to develop appropriate design guidance.
- Evaluate and test European techniques to prevent scour at the “joint” between articulating mattresses and a bridge pier when these products are used as a pier scour countermeasure.

3.3 TECHNIQUES TO ADDRESS ENVIRONMENTAL ISSUES

- Consider risk to the structure, lives, or property in applying environmental policy to bridge scour protection and countermeasures.
- Integrate the consideration of management strategies such as allowing natural adjustment and relocation into the scour and channel instability engineering design process.
- Evaluate and test bioengineering and biotechnical engineering techniques as bridge scour countermeasures for

situations where public safety considerations would not preclude their use.

CHAPTER 4

RECOMMENDATIONS AND IMPLEMENTATION PLAN

This chapter provides recommendations for adapting several elements of European practice to improve U.S. capabilities to deal with stream instability and bridge scour problems on a high priority basis. An implementation plan is also suggested to ensure that the technology acquisition activities initiated by the scanning review will continue and will be disseminated to bridge owners and their engineering staff.

4.1 HIGH-PRIORITY RECOMMENDATIONS

4.1.1 Riprap and Filters

The use of riprap (i.e., armor stone in combination with a geotextile or granular filter) is by far the most common scour and stream instability countermeasure in all countries visited in Europe. Current policy in the United States considers riprap placed at bridge piers to be only a temporary countermeasure against pier scour, and guidance dictates that riprap placed at bridge piers must be monitored by periodic inspection or with fixed instruments. This policy derives from experience with the difficulty of adequately sizing riprap to withstand the turbulence and hydraulic stress generated in the vicinity of a bridge pier, particularly under flood-flow conditions. The failure of the Schoharie Creek bridge in 1987 (attributed to the cumulative loss of riprap around a spread footing foundation) and numerous instances on sandbed channels (where large pier riprap has been swept downstream or loses its effectiveness as it is buried in the sandbed) have substantiated the need for a conservative policy when considering riprap as a pier scour countermeasure.

During the scanning review, it was apparent that European counterparts in the countries visited consider riprap as a permanent pier scour countermeasure. The difference between U.S. and European practice is not necessarily derived from the availability of better techniques for sizing riprap (although consideration of turbulence intensity could lead to more refined riprap design), but rather from the higher standard of care and quality control in placing the stone and providing an appropriate filter on sandbed channels. In addition, European practice includes inspection and monitoring to verify that riprap is performing properly. Contractors in Europe have developed specialized pontoons (barges) for placing riprap accurately and in the appropriate thickness (Figure 9), and, if necessary, each stone is placed individually to optimize performance in critical locations (e.g., the Eastern Scheldt Barrier in the Netherlands, Figure 8).

Equally important for the confidence that European hydraulic engineers have in the use of riprap as a permanent local scour countermeasure is their use of innovative techniques for placing an effective filter beneath the riprap in flowing or deep water. The use of large geotextile sand containers at the Eidersperrwerk in Germany (Figure 13), the use of a geotextile mattress filled with granular filter material at the Eastern Scheldt Barrier in the Netherlands, and the use of fascine sinker mats (Figure 14) at both locations are examples of these techniques. The availability of testing apparatus to ensure that geotextiles will perform as required (Figures 11 and 12) and development of specific codes to guide the design and installation of geotextiles *(31, 32, 33, 34)* contribute to the success of these installations.

As state DOTs in the United States develop Plans of Action for their scour-critical bridges, improved techniques to use riprap effectively as a pier scour countermeasure could result in significant savings, particularly where the only alternative may be rehabilitation or replacement of the affected bridge. A high-priority evaluation of European practice for the design and installation of riprap with an appropriate filter as a permanent pier scour countermeasure is warranted.

4.1.2 Partially Grouted Riprap

Current practice in the United States discourages the use of grouted riprap, primarily because grouting converts a flexible revetment material into a rigid mass susceptible to undermining and failure. The scanning review team members are aware of only a few instances in the United States (e.g., an installation by CALTRANS) where anything other than total grouting of the riprap layer has been attempted. Ongoing tests in Germany at BAW, experience on German inland waterways *(27)*, and development of design guidance for partial bituminous and cement grouted riprap *(14)* indicate that design guidelines and installation experience are available or are being developed in Europe. These European design guidelines, specifications, and installation techniques for partially grouted riprap should be investigated on a high-priority basis.

4.1.3 Risk Analysis

The scanning review team members found that some form of risk analysis is used to determine the level of effort and investment in countermeasure design and installation in all countries visited. In Switzerland, for example, a differentiation of protection objectives is applied (Figure 2), and an appropriate degree of safety is selected according to the importance of the structure to be protected *(23)*. This contrasts with the general approach in the United States of using a 100-year design flood and 500-year check flood for all structures. However, the use of a super flood, such as the

200-year flood in the United Kingdom, or the 1,000 year flood for sea defenses in the Netherlands, for scour evaluations appears to be standard practice in Europe. Annandale *(42)* has outlined techniques for applying risk analysis to the bridge failure problem.

The use of fault tree analysis (Figure 3) was recommended in several countries visited. Johnson *(43)* has suggested techniques to apply fault tree analysis techniques to the analysis of a bridge failure resulting from scour and channel instability.

The increased use of risk analysis in countermeasure selection and design and the use of techniques such as fault tree analysis could result in more economical design of bridge scour countermeasures as state DOTs develop Plans of Action for scour-critical bridges. These concepts should be evaluated and disseminated, as appropriate, to bridge owners in the United States.

4.1.4 Scour Prediction

In the United States, the problems of estimating scour at wide piers, the time rate of scour in cohesive and non-cohesive materials, and the interaction of the various scour components are among the most pressing U.S. research needs in scour. The Dutch *Scour Manual (8)*, in particular, provides a comprehensive treatment that builds on earlier European literature on scour. A detailed review of the Dutch *Scour Manual* and other comprehensive treatments of the scour process *(9, 13)*, is warranted. Appendix D presents insights on two high-priority research needs: the time scale (characteristic time) for development of scour, and scour at wide piers as an example of the potential benefits of a more thorough review of the European literature on scour.

4.1.5 Update of the FHWA HECs

In the United States, bridge scour technology is contained primarily in three FHWA HECs:

- HEC-18 Evaluating Scour at Bridges,
- HEC-20 Stream Stability at Highway Structures, and
- HEC-23 Bridge Scour and Stream Instability Countermeasures.

FHWA is revising and updating these manuals, with draft revisions scheduled for completion in October 1999. The scope of work for these revisions includes reviewing and evaluating the European literature on bridge scour and stream instability obtained by the scanning review team members during the scanning review. It is anticipated that the update of the three HECs will be followed by revisions to the two National Highway Institute (NHI) training courses on bridge scour: NHI Course No. 13046—Stream Stability and Scour at Highway Bridges, and NHI Course No. 13047—Stream Stability and Scour for Bridge Inspectors.

The FHWA HECs and NHI training courses represent the most efficient means of disseminating new technology to state DOTs and other bridge owners. Information gained from the countermeasures scanning review on European practice that does not require further research or laboratory or field testing should be incorporated into the current revisions of the HECs and training course materials.

Other activities to continue the technical contacts with counterparts in Europe and disseminate information gained during the scanning review are outlined in the Implementation Plan that follows.

4.2 IMPLEMENTATION PLAN

During the final scanning review team meeting, initial steps were taken to develop an implementation plan. Since returning from the scanning review, several implementation activities have been completed and others are being planned. This section summarizes these activities and suggests other implementation actions that should be considered for the future.

4.2.1 Implementation Activities Accomplished

- In November 1998, shortly after returning from the scanning review, Mr. William Hulbert, South Carolina DOT Scanning review team member, made a presentation on initial findings at the AASHTO meeting in Boston.
- Mr. Jorge Pagan of FHWA and Dr. Peter Lagasse of Ayres Associates submitted an abstract for a paper on scanning review results to the American Society of Civil Engineers Water Resources Division Specialty Conference scheduled for August 1999 in Seattle, Washington. The paper has been accepted for presentation and publication in the conference proceedings.
- In January 1999, during the annual TRB meeting in Washington D.C., Dr. Peter Lagasse of Ayres Associates presented a short overview of initial findings from the scanning review to the Hydraulics, Hydrology, and Water Quality (A2A03) committee. A more detailed presentation of findings is scheduled for the committee's mid-year meeting in June 1999.
- In March 1999, Mr. Sterling Jones of FHWA made a presentation on the initial findings to the FHWA's International Coordination Group in Washington, D.C.
- FHWA and NHI authorized presentation of NHI Course No. 13046 in Wallingford, United Kingdom, from April 28 through April 30, 1999.
- A Stream Stability and Scour course was held in cooperation with the H.R. Wallingford Laboratories in the United Kingdom. Its primary purpose was to build on the rapport established with scour researchers and practitioners during the visit to the United Kingdom. The course was staffed with FHWA and Ayres instructors to increase the opportunities for productive exchange.

4.2.2 Implementation Activities Planned

Among the implementation suggestions at the final scanning review team meeting were the following actions:

- Incorporate new technology into the FHWA planned update of HEC-18, 20, and 23 and in NHI planned revisions to Stream Stability and Scour at Bridges courses (NHI No. 13046 and 13047) and Highways in the River Environment course (NHI No. 13010).
- Present findings from the scanning review at the following meetings or conferences:

  — AASHTO Bridge Conference, San Diego, May 1999 (Pagan)
  — AASHTO Special Committee on Activity Coordination meeting, Washington, D.C., May 1999 (Pagan)
  — Western Regional Hydraulic Engineers Conference, Lake Tahoe, May 1999 (Lagasse)
  — AASHTO Bridge Conference, San Diego, California, May 1999
  — TRB 5th Bridge Conference, Tampa, Florida, April 2000 (to include Countermeasures Scanning Review Overview (Hulbert, Ghere, and Bryson), Wide Piers (Jones et al.), Risk Analysis (Jones et al.), Comprehensive Scour Evaluation Methodology (Lagasse et al.)
  — International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Year 2000 Conference, Melbourne, Australia

4.2.3 Implementation Activities Suggested

- Explore opportunities to reach the Association of General Contractors regarding techniques, equipment, quality control, specifications, and so forth for riprap and other countermeasure placement.
- Seek support for a study of AASHTO riprap specifications and work with AASHTO on recommendations for improvement of installation and quality control techniques.
- Evaluate European time rate of scour concepts to establish limits on the amount of scour that can reasonably be expected to occur when hydraulic stresses are of short duration (e.g., a coastal estuary bridge during a hurricane storm surge). The procedure suggested in Appendix D could result in significant savings for the planned widening of I-95 crossings in Georgia and should be evaluated further. If appropriate, results should be included in the next edition of HEC-18.

APPENDIX A

ORGANIZATIONS AND CONTACTS

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Roads Bridge Research Institute, Zmigrod
Wysokowski, A., Dr.Ing.

Dr. Wysokowski joined the Panel in Karlsruhe and participated in the scanning review during our three days in Germany. He made a presentation on the floods of July 1997 and July 1998 on the Oder River, which forms the border between Germany and Poland, in which hundreds of bridges were damaged and thousands declared unsafe as a result of subsequent scour evaluations. He provided two detailed reports, in Polish, showing damages and recovery efforts.

APPENDIX B

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

Swiss Organizations

ASTRA	Federal Office for Highways
BAV	Federal Office for Transport
BWW	Federal Office for Water Management
ETH	Swiss Federal Institute of Technology
SBB	Swiss Federal Railways
VAW	Laboratory of Hydraulics, Hydrology, and Glaciology

German Organizations

BAST	Federal Highway Research Institute
BAW	Federal Waterways Engineering and Research Institute
DVWK	German Association for Water Resources and Land Improvement

British Organizations

HA	Highways Agency
NRA	National Rivers Authority

United States Organizations

AASHTO	American Association of State Highway and Transportation Officials
DOT	Department of Transportation
FHWA	Federal Highway Administration
NCHRP	National Cooperative Highway Research Program

NHI	National Highway Institute
SHA	State Highway Agency
TRB	Transportation Research Board

General Terminology

HEC	Hydraulic Engineering Circular (FHWA)
HEC	Hydrologic Engineering Center (U.S. Army Corps of Engineers)
NBIS	National Bridge Inspection Standards (US)
PIANC	Permanent International Association of Navigation Congresses
PONTIS	Bridge Management System Software (U.S.)
SOWAS	Soil, Water, Structure

APPENDIX C

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APPENDIX D

DESIGN METHODOLOGY

TIME RATE OF SCOUR

An area of European research that could be extremely useful to U.S. hydraulic engineers is time dependent scour. The Dutch *Scour Manual (8)* includes methods for predicting the rate of scour development. The presentation at Wallingford, England also included the topic of rate of pier scour. In each case, a characteristic time was defined that was related to a characteristic depth of scour. Although the characteristic depths and times were defined differently, each is related to the critical (incipient motion) velocity, the approach velocity and a coefficient related to turbulence intensity. The British define the coefficient as the ratio of maximum velocity around a pier to the approach velocity and the Dutch (8) define the coefficient as the relative turbulence intensity. These concepts may be useful to scour practice and scour research in the U.S.

In tidal areas in the U.S., hurricane storm surges often produce extreme hydraulic conditions. Computing ultimate **contraction** scour amounts for these conditions may not be reasonable based on the short duration (approximately 3 hours) of the surge. Based on equations in the Dutch *Scour Manual (8)*, the time development of a contraction scour hole was estimated for a bridge in the southeastern U.S. (Georgia coast) for a 500-year storm surge. To provide confirmation of these results, the Yang sediment transport equation was used to compute contraction scour hole development based on the erosion of the scour hole equal to the transport capacity in the contracted bridge opening. The scour rates for this situation are shown in Figures D1 and D2. Figure D1 shows the full development of the scour with time plotted on a logarithmic axis, and Figure D2 shows the first 100 hours of development with time plotted on an arithmetic axis. The scour rates predicted by the two methods are extremely similar and indicate that the scour that could be generated in the few hours available during a storm surge is significantly less than the ultimate contraction scour condition.

Also shown in Figures D1 and D2 is the development of a **pier** scour hole for the same hydraulic conditions. Figure D2 shows that the pier scour hole reaches 90 percent of ultimate scour in the first 20 hours while the clear water **contraction** scour reaches only about 30 percent of ultimate scour.

The Dutch methods are based on clear water scour and the conditions used to test the Yang equation were close to clear water. The *Scour Manual (8)* indicates that under live bed conditions, scour reaches ultimate conditions more rapidly and that the ultimate scour is less than the equivalent clear water case which is consistent with current U.S. guidance. Figure D3 shows the development of contraction scour

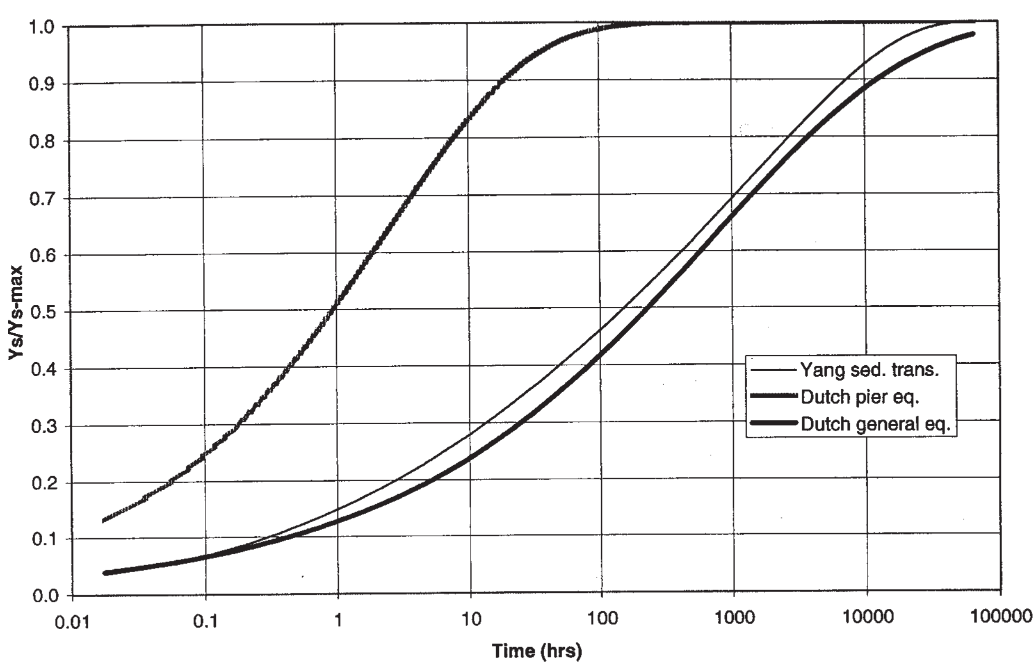

Figure D1. Time development of scour.

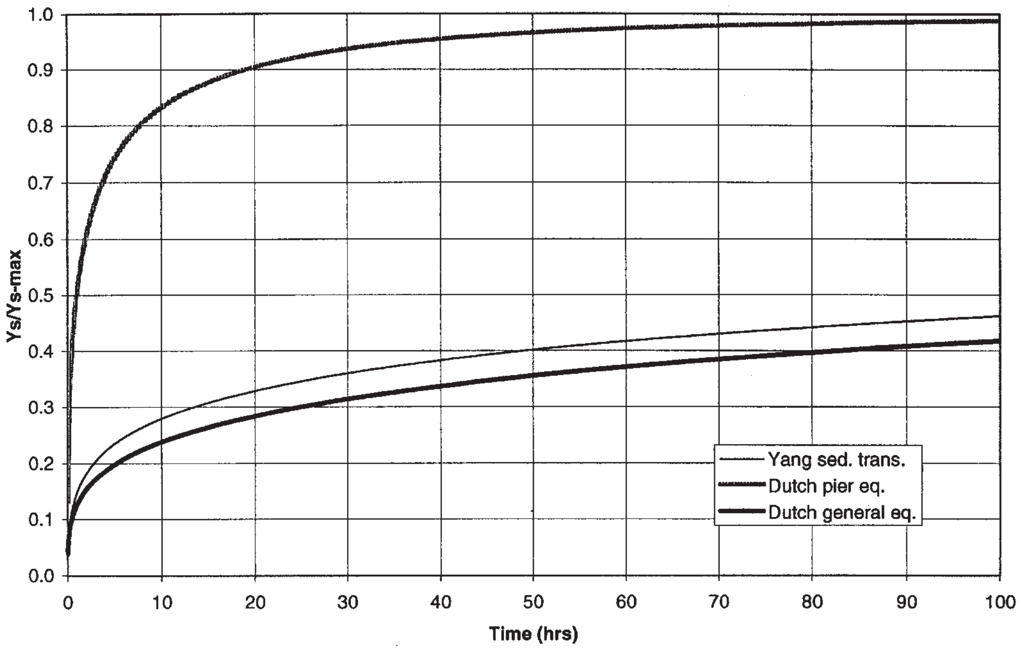

Figure D2. Initial scour development.

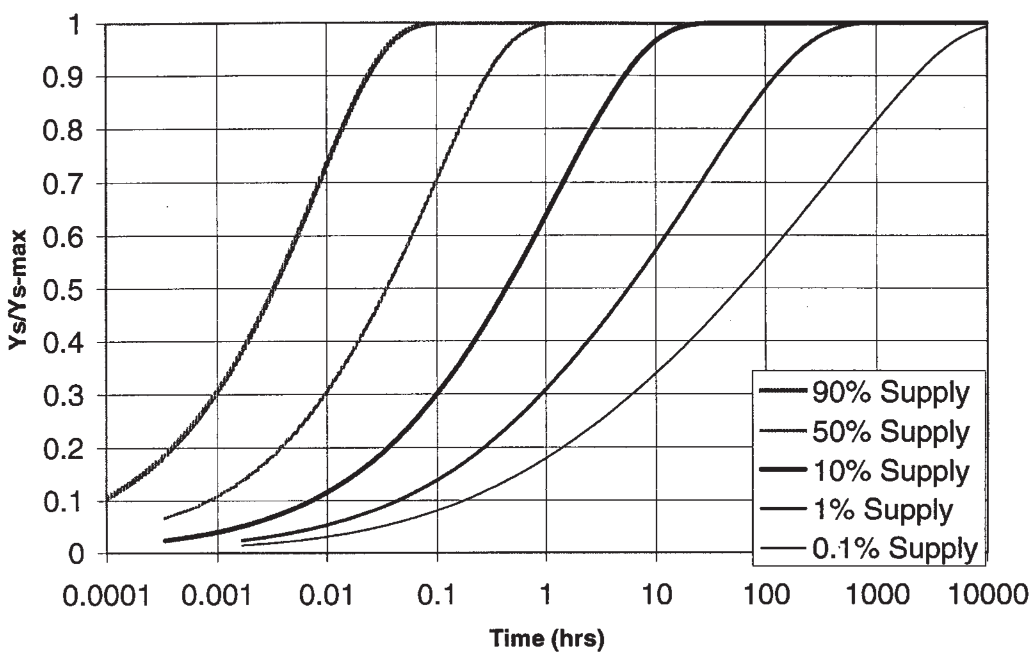

Figure D3. Contraction scour development with sediment supply.

(using the Yang equation) under varying amounts of upstream sediment supply relative to the transport capacity in the bridge opening. For the case shown, if the upstream channel is supplying 50 percent of the contracted section transport capacity, the scour hole reaches its ultimate depth in approximately 1 hour. Based on this review, it appears that contraction scour should be reviewed on a case-by-case basis to assess the level of scour that could occur over a short time.

The time-dependent scour information obtained during the scanning tour has been extremely useful on several ongoing tidal scour studies for bridge rehabilitation. Significant cost savings are expected for bridge rehabilitation and new bridge design based on this topic alone.

SCOUR AT WIDE PIERS

In commenting on the initial Summary Report for the scanning review, Mr. Henk Verheij of Delft Hydraulics in the Netherlands made the following observations.

In the past, Delft Hydraulics developed a formula for calculating scour at wide piers (and slender piers), namely. the Breusers formula (Breusers, Nicollet, and Shen, “Local Scour Around Cylindrical Piers,” *Journal of Hydraulic Research*, Vol. 15, no. 3 [1977] pp. 211-252):

$$y_s = 1.5b\tanh(h_o / b)$$

with y_s = scour depth, b = pier width, and h_o = water depth.

This formula is not mentioned by Breusers and Raudkivi in their 1991 manual, but it is in the *Scour Manual* by Hoffmans and Verheij on page 114 (1997).

Depending on the ratio h_o/b this formula predicts scour for slender piers ($h_o/b > 1$) or wide piers ($h_o/b < 1$):

wide piers:	$b/h_o > 1$ resulting in:	$y_s = 1.5\ h$
slender piers:	$b/h_o < 1$ resulting in:	$y_s = 1.5\ b$

These **Digests** are issued in order to increase awareness of research results emanating from projects in the CRP. Persons wanting to pursue the project subject matter in greater depth should contact the Cooperative Research Programs Staff, Transportation Research Board, 2101 Constitution Ave., NW, Washington, DC 20418.

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