NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 251

ASSESSMENT OF DEFICIENCIES AND PRESERVATION OF BRIDGE SUBSTRUCTURES BELOW THE WATERLINE

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **251**

ASSESSMENT OF DEFICIENCIES AND PRESERVATION OF BRIDGE SUBSTRUCTURES BELOW THE WATERLINE

M. C. RISSEL, D. R. GRABER, M. J. SHOEMAKER and T. S. FLOURNOY
Byrd, Tallamy, MacDonald and Lewis
Falls Church, Virginia

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

AREAS OF INTEREST
- STRUCTURES DESIGN AND PERFORMANCE
- MAINTENANCE
- (HIGHWAY TRANSPORTATION)
- (PUBLIC TRANSIT)
- (RAIL TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. OCTOBER 1982

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

NCHRP REPORT 251

Project 10-16 FY '81
ISSN 0077-5614
ISBN 0-309-03421-3
L C Catalog Card No 82-62041

Price: $8.40

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council, acting in behalf of the National Academy of Sciences Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors

Each report is reviewed and processed according to procedures established and monitored by the Report Review Committee of the National Academy of Sciences Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences

The Transportation Research Board evolved from the 54-year-old Highway Research Board The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society

Special Notice

The Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. PB83-170159

FOREWORD

By Staff
Transportation
Research Board

This report contains the findings of a comprehensive evaluation of: (1) methods of assessing the significance of bridge deficiencies below the waterline and (2) methods of arresting deterioration in bridge elements below the waterline. The report, including recommendations that are applicable immediately, will be of interest to engineers, researchers, and others concerned with maintenance, repair, and rehabilitation of bridges below the water or in the splash zone.

Federal and state legislation requires periodic inspection and appraisal of all bridge elements. A substantial amount of information is available on repair methods for superstructures and substructures above the waterline, but procedures for use below the waterline have received little emphasis, and application is complicated by inaccessibility. As a result, deficiencies including scour and structural distress, damage, and deterioration sometimes remain undetected or are endured until the potential for a major failure becomes apparent. Information has been needed to guide engineers in assessing the condition of bridge elements below the waterline and in selecting appropriate methods to arrest further deterioration.

This report contains the findings of NCHRP Project 10-16, "Assessment of Deficiencies and Preservation of Bridge Substructures Below the Waterline." The objectives of this research were: (1) to develop improved methodology for evaluating the effects of below-the-waterline deficiencies on the structural capacity of the substructure, and (2) to develop solutions to specific deterioration problems that are found in bridge substructures below the water surface and in the splash zone. NCHRP Project 10-16 extended the findings of research completed earlier and published as *NCHRP Synthesis of Highway Practice 88*, "Underwater Inspection and Repairs of Bridge Substructures."

Current practices in structural strength evaluation techniques for bridge substructures below the water surface were evaluated with particular emphasis on quantifying the consequences of the deficiencies on the structural integrity of the bridge. A rating system for identifying the urgency of corrective action is presented. State-of-the-art methods used to arrest deterioration below the water surface and in the splash zone were evaluated and promising techniques identified. Several new or improved methods to arrest deterioration were also conceptualized.

971950 PB83-170159 82-025 HN-TE7.N25 #251
Assessment of Deficiencies and Preservation of Bridge Substructures Below the Waterline
(Final rept.)
Rissel, M. C. ; Graber, D. R. ; Shoemaker, M. J. ; Flournoy, T. S.
Byrd, Tallamy, MacDonald and Lewis, Falls Church, VA.
Corp. Source Codes: 058421000
Sponsor: Transportation Research Board, Washington, DC.; American Association of State Highway and Transportation Officials, Washington, DC.; Federal Highway Administration, Washington, DC.
Report No.: NCHRP-251; ISBN-0-309-03421-3
Oct 82 90p
Sponsored in part by American Association of State Highway and Transportation Officials, Washington, DC., and Federal Highway Administration, Washington, DC. Library of Congress catalog card no. 82-62041. Also pub. in ISSN-0077-5614.
Paper copy also available from Transportation Research Board, 2101 Constitution Ave., NW, Washington, DC. 20418.
Languages: English Document Type: Journal article
NTIS Prices: PC A05/MF A01
Country of Publication: United States
Journal Announcement: GRAI8313
Contract No.: NCHRP-10-16

This report examines the state of the art of the assessment of the effects of underwater deficiencies on bridge substructures. Also reported are methods to arrest the deterioration of concrete substructure units of all types in and below the splash zone caused by abrasion, corrosion, freeze-thaw and chemical attack. Proposed guidelines for a rating system stressing the urgency of corrective action for assessing various kinds of underwater deficiencies occurring to bridge substructures are developed and presented. Consideration was also given to developing practical methods to predict reduced structural capacity as a result of underwater deficiencies. This work was accomplished with a literature search, a telephone survey of 26 states and field visits to six of those states.

Descriptors: *Highway bridges; *Pile foundations; *Concrete durability; Water erosion; Deterioration; Protective coatings; Substructures
Identifiers: NTISNASTRB; NTISDOTFHA
Section Headings: 13B (Mechanical, Industrial, Civil, and Marine Engineering--Civil Engineering); 13C (Mechanical, Industrial, Civil, and Marine Engineering--Construction Equipment Materials and Supplies); 50A (Civil Engineering--Highway Engineering); 50C (Civil Engineering--Construction Equipment, Materials, and Supplies)

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-16 by Byrd, Tallamy, MacDonald and Lewis, with Martin C. Rissel as the Principal Investigator, and Donald R. Graber as the Assistant Principal Investigator. Michel J. Shoemaker and Thomas S. Flournoy were staff investigators. Mr. Shoemaker now is employed by Tryck, Nyman, and Hayes, Anchorage, Alaska.

Cooperation was received from all state personnel contacted during the field visits that were conducted. Particular effort was given by Mr. E. William Ensor, Jr., Chief of Bridge Inspection and Remedial Engineering, Maryland Department of Transportation; Mr. John Wood, Structure Maintenance Engineer, Oregon Highway Division; Mr. James N. Welch, Bridge Maintenance Engineer, Idaho Transportation Department; Mr. John D. Wood, Assistant to Structures Maintenance Engineer, Massachusetts Department of Public Works; Mr. Mrutyunjaya Pandi, Structure Repairs and Reconstruction Engineer, Louisiana Department of Highways and Mr. Larry Davis, Bridge Maintenance-Planning Engineer, Florida Department of Transportation

Time and effort were given by all those who attended the "Brainstorming" session. Outside personnel included: Doctors Alfred Marzocchi and Anil K. Rastogi of Owens-Corning Fiberglas, Messrs Phillip T. Scola and Wade F. Casey of the Naval Facilities Engineering Command, and Mr. Schuyler B. Smith of Dow Corning Corporation.

Others who were particularly helpful in special areas were: Mr. Robert P. Brown, State Corrosion Engineer, Florida Department of Transportation; Dr. Roger D. Browne of the Taylor Woodrow Research Laboratory, United Kingdom, Mr. Kenneth C. Clear of the FHWA's Office of Research; and Mr. M. Sharif Aggour of the University of Maryland.

Assessment of Deficiencies and Preservation of Bridge Substructures Below the Waterline

SUMMARY

The research results presented here are the product of an examination of the state-of-the-art practices in the structural evaluation of underwater deficiencies of bridge substructures and the development of an improved methodology for evaluating the effects of below-the-waterline deficiencies. The research was conducted under NCHRP Project 10-16, and extends previous research developed under NCHRP Project 20-5 (Topic 10-08), which resulted in NCHRP Synthesis of Highway Practice 88. This investigation (Project 10-16) pertains to the techniques used to inspect bridge elements below the waterline and covers both present and new or improved methods and materials used to maintain, repair, and arrest deterioration under water. The findings are summarized in these areas in the following.

A vast amount of information exists on inspection techniques for evaluating concrete, steel, and timber under water. The inspection of concrete under water normally includes visual assessment, measurement of physical dimensions, and soundings. Because of the expense, cores are usually taken under water only when other evidence indicates that further investigation is warranted. Cores are normally used to determine compressive strength and chloride content and penetration, even though they permit a wide variety of other physical and chemical analyses to be performed.

Voltage potential readings of the reinforcing steel are sometimes taken under water. The readings only indicate whether or not corrosion is active and the extent of the concrete surface involved. The most satisfactory results are obtained when the readings are used in conjunction with a chloride penetration analysis of a core sample.

Two additional devices are presently being developed to evaluate concrete: (1) a polarization resistance device that measures the rate of corrosion--several methods are presently being tested for field use in-the-dry; and (2) a cat scanner for testing concrete piles under water--this device is being field tested by the Navy and it will be able to show density, corrosion, and internal structure.

The inspection of steel under water normally includes visual assessment, measurement of physical dimensions, and sounding bolts and rivets. Coupon samples for further testing are taken under water, on occasion, if evidence indicates that this is warranted. Ultrasonic testing has also been employed; however, it has several drawbacks when applied under water. The leader in underwater inspection of steel is the maritime industry, which developed this field as an alternative to dry-dock inspection. Other methods developed by this industry for detecting cracks include magnetic particle testing, radiographic inspection, and acoustic holography.

The inspection of timber structures under water normally includes visual assessment, measurement of physical dimensions, soundings, pointed probe resistance testing, use of a brace and bit, and use of an increment borer. Sonic pulse velocity testing is also available for application under water. Several commercial devices are on the market and a number of contractors offer underwater inspection services using this technique.

The Federal Highway Administration's Structural Inventory and Appraisal (SI&A) Item 60 is the rating system used to rate substructure condition. However, none of the state personnel interviewed favored using the Item 60 condition statements as a

method to assess underwater deficiencies for the purpose of prioritizing maintenance projects.

This is understandable because the SI&A condition statements were developed as a means of establishing priorities for rehabilitation projects. Accordingly, in order to prioritize maintenance projects based on the assessment of underwater deficiencies and the urgency of corrective action, the research team developed a maintenance urgency index. The method of arriving at the maintenance urgency index is capsulized in a proposed guideline booklet included in Appendix G.

This booklet contains guidelines to describe various types of substructure elements in various states of deterioration. Observed underwater deficiencies are to be compared to the guidelines to select an initial assessment. The initial assessment, which can range from zero to 9, may then be modified by a factor ranging +2 to -2 to account for the effects of climate and other factors. This final number is the Maintenance Urgency Index. It, in turn, prescribes the type of action to be taken by inspection personnel in the field as well as by maintenance forces in scheduling work that is to be performed. It should be noted that this booklet is <u>not</u> to be construed as a replacement for the rating system now used to rate the substructure condition for Item 60 of FHWA's "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (SI&A), but rather it is meant as an adjunct to it. The SI&A rating system is required for consistency of approach for funding eligibility from a reconstruction viewpoint. The methods presented herein are only intended to provide a more consistent approach to the process of assessing deficiencies from a maintenance viewpoint.

Substantial information was also found to exist on concrete deterioration under water. A primary active zone is present in the splash zone. A secondary active zone exists at the mud line. The condition of the concrete cover and the availability of oxygen are the major factors in the corrosion of reinforcing steel. Chemical attack is usually a slow process and significant in itself in that it destroys the concrete cover over the reinforcing steel. Industrial waste was found to be of less concern.

Deterioration was associated with three stages: initiation, propagation, and destruction. The repair techniques discussed in the following are grouped under these three stages according to when they are the most cost effective.

Hydraulic training was found to be of some help in arresting abrasion, although ponding and riprap are the most effective methods. Penetrating scalants are ineffective under water.

Surface coatings have several problems including: bond to the concrete surface, wick action, and encapsulation of the concrete section. Vapor-permeable coatings can be helpful against encapsulation. Epoxy resin surface coatings have had only partial success because they must be applied with very strict controls. Veneers are used for cases of extreme chemical attack.

Wraps are good for severe chemical attack. This method is quick and economical. Resin-impregnated-fiberglass cloth is costly and difficult to use. Fabric jackets are quick and econmical, although they deform in water currents. Both metalic and nonmetalic jackets have had limited success.

Sealing cracks with pressure injected grout has been successfully used under water. A nonstructural sacrificial concrete collar can be cast around structural concrete usually at the waterline. This method is expensive and used only in extreme conditions.

A variety of grouts are available to restore large areas of deterioration and/or section loss in the splash zone. Use of the proper grout can be an effective measure.

A sacrificial zinc anode can be attached directly to exposed reinforcing steel. This method is quick, simple, and arrests corrosion for up to 2 years.

A "brainstorming" session was conducted with representatives of industry and government to generate new or improved methods to arrest concrete deterioration under water. Economical methods were sought that could be applied without the need for extensive evaluation of the concrete.

Several ideas were offered at the brainstorming session, including a multiple tape system that could be wrapped around a pile or column. Several coatings were suggested, such as cycloaliphatic polyurethane silicone elastomeric membrane, silica gel, liquid plastic coatings, silicone latex emulsions, and flaked glass. Other suggestions included a dewatering cofferdam to apply preservation procedures in-the-dry, a floating innertube device to stop ice abrasion, litmus-paper-type indicators to identify chemical attack, a chemical filter, a bubbler curtain to stop ice formation, a vulcanized rubber wrap, greasing the pier to make it hydrophobic, and applying an electric charge to drive out ions.

The multiple tape system was later conceptualized as consisting of four separate tapes--abrasion tape, rubberized asphalt tape to arrest chemical attack, plastic foam tape to arrest freeze-thaw, and conducting tape to arrest corrosion--and two tape applicators. The dewatering cofferdam was considered along with two types of sprayers to be used inside of it for the application of sealants and coatings.

Chapter One

INTRODUCTION

BACKGROUND

Since 1761 when Samuel Sewell constructed the first highway bridge of importance in York, Maine (1), engineers and contractors in the United States have developed a long history of designing and constructing ever larger, more imposing, and more efficient bridges. However, when the Silver Bridge over the Ohio River between West Virginia and Ohio failed, causing loss of life in December of 1967, the point was made with startling clarity that insufficient attention was being devoted to existing structures.

Older structures had been designed for one set of conditions while technological changes and rapid growth have imposed other conditions that are considerably different. Additionally, time and weather were taking their toll and many of the bridges that had served so well and for so long could no longer be trusted to carry the steadily increasing loadings of modern traffic. Congress took recognition of this fact by including a requirement for regular bridge inspection in the Federal-Aid Highway Act of 1968 (Public Law 90-495, SEC. 26, 82 Stat. 815).

The Federal Highway Administration (FHWA) of the U.S. Department of Transportation published policies and procedures to implement the inspection process, and a Manual for Maintenance Inspection of Bridges was published in July 1970, by the American Association of State Highway and Transportation Officials (AASHTO). The requirements and procedures have been updated periodically until the inspection program has now become a well-defined and orderly system that for the most part serves its intended purpose with adequate precision. Requirements for personnel, procedures, and fequency of inspection are sufficiently detailed to ensure that bridge deficiencies will be recognized and repaired in a timely fashion.

Because the failure precipitating the National Bridge Inspection Program occurred to a superstructure element, and deficiencies to superstructures are most visible, the greatest initial attention was directed to that portion of the structure despite the fact that nothing in FHWA's "Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridges" (SI&A) guideline either encourages or discourages substructure inspection as compared with superstructure inspection. Any emphasis, therefore, was the responsibility of the inspection agency and not derived from the material provided to them. Several states recognized that equally unsatisfactory conditions could exist out-of-sight, under water, and initiated vigorous underwater inspection and repair programs.

In recent years, many additional states and jurisdictions that are charged with the maintenance of structures have developed and regularly operate underwater inspection programs. Figure 1 shows an underwater inspector at work.

Interest in both inspection methods and systems to repair and prolong the life of aging substructure units in and below the splash zone is continuing to increase. This has occurred not only because of the evolutionary process of improvement in bridge inspection and repair, but, even more, because of the increasing need to construct off-shore structures in connection with oil and gas exploration and drilling activities.

In the area of underwater inspection of bridges, jurisdictions that are active in this field use a variety of procedures, equipment, and techniques. Due at least in part to this variety as well as a low level of inspection effort, there has been a lack of consistency in both developing and evaluating information obtained from underwater inspections.

Federal and state legislation requires periodic inspection and appraisal of all bridge elements. A substantial amount of information is available on repair methods for superstructures and substructures above the waterline, but procedures for use below the waterline have received little emphasis and application is complicated by inaccessibility. As a result, deficiences including scour, structural distress, damage, and deterioration are sometimes undetected or endured until the potential for a major failure becomes apparent. Information is urgently needed to guide engineers in assessing the condition of bridge elements below the waterline and in selecting appropriate methods to arrest further deterioration.

OBJECTIVES

This study is intended to extend previous research developed under NCHRP Project 20-5 "Synthesis of Information Related to Highway Problems," Topic 10-08 entitled "Below-the-Waterline Inspection and Repair of Bridge Substructures," which resulted in a two-part report on current practice (NCHRP Synthesis of Highway Practice 88). The first part identifies problems found in substructure components and evaluates procedures, equipment, and techniques currently used to inspect bridge elements below the water surface. The second part covers methods and materials used for underwater maintenance and repair of bridge substructures.

Figure 1. Underwater inspector.

The procedures, equipment, and techniques discussed in this report will overlap, in part, that found in the previous report. This is necessary to provide continuity to the subject and to permit this report to stand alone as an independent, self-contained document.

The objectives of this project are:

1.To develop improved methodology for evaluating the effects of below-the-water-line deficiencies on the structural capacity of the substructure.

2.To develop solutions to specific deterioration problems that are found in bridge substructures below the waterline and in the splash zone.

APPROACH

Literature Search

The initial effort in fulfillment of the project objectives was to conduct a literature search and review. The search was conducted in the libraries of the Federal Department of Transportation, the Transportation Research Board, and the Library of Congress (see App. B for a complete list). In addition, a Highway Research Information Service (HRIS) computer search was conducted. Figure 2 graphically depicts the research approach.

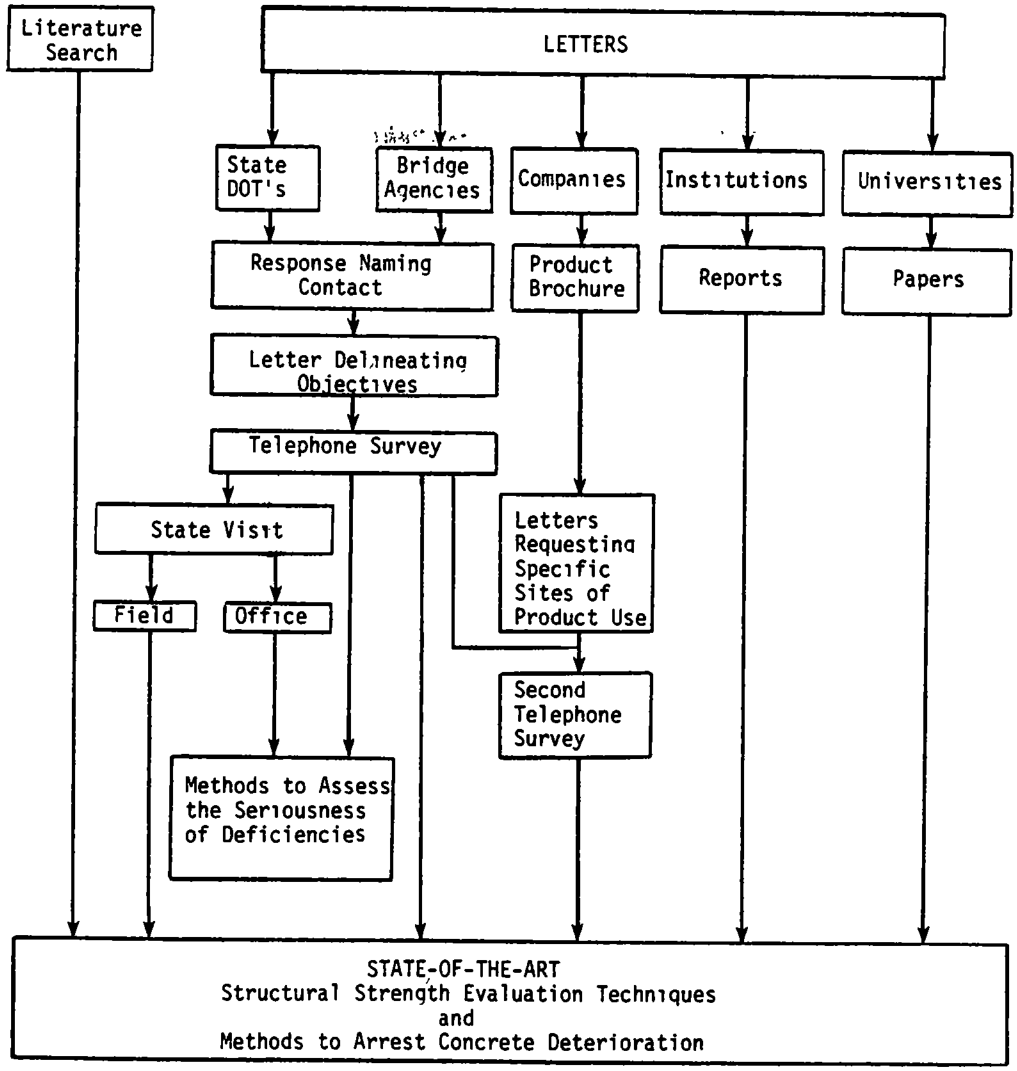


Figure 2. Research approach.

Correspondence

The second basic method of evaluating state-of-the-art practice was by correspondence. Letters were written to state departments of transportation (or highway agencies), universities, institutes, trade associations, councils, laboratories, business concerns, bridge and port authorities, railroads and appropriate government agencies, both domestic and foreign. Standard formats were followed with minor adjustments made to compensate for differences of interest. Addressees are given in Appendix B.

Telephone Survey

Those agencies indicated in Topic 10-08 of NCHRP project 20-5 as having an active underwater inspection program were selected for a telephone survey. The survey consisted of a series of questions asked following a guide to assure consistency. The answers received from the telephone survey were then collected and summarized.

State Visits

A personal visit by the principal investigator was made to those agencies selected in order to interview appropriate personnel and to make field visits to sites to review both the deterioration of substructure units and the corrective measures taken. During the interview portion, information received as a result of the telephone survey was reviewed and additional comments where recorded.

As part of the visit, series of typical sketches were generated which approximated those that would be developed as a result of an underwater inspection. These were combined with a series of descriptions of various types of deficiencies in the form of "suggested guidelines" for various levels of severity tied to a numerical rating of the substructure condition. In this way, it was possible to standardize the level of seriousness of a deficiency and the rating number given, utilizing the experience of those individuals with the most "hands on" experience.

For this task, the following substructure types were considered in the development of the descriptions and guideline:

- Pile bent, concrete, steel, and timber.
- Column bent or open pier.
- Solid shaft pier on spread footings.
- Solid shaft pier on piles.

Written information provided by the states in the form of procedural instructions, coding guides, or similar documents was also requested.

Details of repairs that had been made in an attempt to arrest deterioration were discussed during the interview period. Following this, a field visit was made to various sites to view specific types of deterioration that had occurred and the methods used to repair the damage and to arrest further deterioration.

Brainstorming Session

For "new or improved methods to arrest concrete deterioration," a "brainstorming" session was conducted by the research team with representatives from industry and governmental agencies in attendance.

Chapter Two

STRUCTURAL EVALUATION

SI&A BRIDGE INVENTORY

The purpose of the Federal Highway Administration's "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (SI&A) is to develop a bridge inventory data base in order to report to the Congress the number and condition of the nation's bridges for their use in preparing future legislation. The information is also used to inventory Defense Bridges and Critical Highway Facilities for military purposes.

The data are collected as coded items on the SI&A sheet, which is shown in Figure 3. Of the 88 items listed on the sheet, items pertinent to this report are discussed in the following.

Sufficiency Rating Formula

The sufficiency rating is a method of evaluating many factors that are indicative of the sufficiency of a bridge to remain in service. This rating is used as input into the Highway Bridge Replacement and Rehabilitation Program for prioritizing bridge replacement and rehabilitation projects for federal funding.

The sufficiency rating is generated through use of a complicated formula using the input of many factors. Among them are Item 67, Overall Structure Adequacy Appraisal; Item 66, Inventory Rating; Item 64, Operating Rating; and Item 60, Substructure Condition Rating. The final output is a number from zero to 100.

Overall Structure Adequacy Appraisal

Item 67 is the "Overall Structure Condition Appraisal." It is a composite rating representing the average of several factors. The load carrying capacity of the deck, the superstructure, and the substructure as well as the condition rating of the deck, the superstructure, and the substructure are evaluated in relation to the highway system and how they affect the bridge as a unit. The structure is then compared to a new bridge built to the state's current standards for that particular type of highway. The overall structural condition is appraised from zero to 9, taking into account the major structural deficiencies.

Of the total items considered in establishing this appraisal, deficiencies below the waterline constitute a relatively small part. Yet underwater deficiencies are clearly of a critical nature and affect the load carrying capacity. In this case, they can be the determining factor for the overall structure condition appraisal.

Inventory Rating

Item 66 is the capacity rating of the structure to a load level that can safely utilize the structure for an indefinite period of time. The capacity to be recorded is the lesser of the deck, superstructure, or substructure ratings. The code used represents the truck type used in the analysis and the total tonnage of the truck.

STRUCTURE INVENTORY & APPRAISAL SHEET

IDENTIFICATION

1 State
2 Hwy. Div.
3 County 4 City/Town
5 Inventory Route On Under
6 Features Intersected
7 Facility Carried by Structure
8 Structure No
9 Location
10 Min Vert Clearance, Inv. Rte
11 Milepoint
12 Road Section No.
13 Defense Bridge Description
14 Defense Milepoint
15 Defense Section Length
16 Latitude
17 Longitude
18 Physical Vulnerability
19 By-pass, Detour Length
20 Toll Bridge On Toll Road On Free Road
21 Custodian
22 Owner
23 F.A.P. No.

CLASSIFICATION

24 Fed. Aid System
25 Administrative
26 Functional

	By	Date
Transfer of Data		
Maintenance Insp.		
Condition Analysis		
Appraisal		
Cost Estimate		
General Review		

STRUCTURE DATA

27 Year Built
28 Lanes on Str under
29 ADT 30 Year
31 Design Load
32 Appr. Rdwy Width W/sh'ld
33 Br Median None Open Closed
34 Skew
35 Structure Flared Yes No
36 Traffic Safety
37
38 Navigation Control Yes No
39 -Vertical ft.
40 -Horizontal ft.
41 Open-Closed-Posted

42 Type Service
43 Structure Type-Main
44 -Approach
45 No. of Spans-Main
46 -Approach
47 Total Horiz. Clearance ft
48 Max. Span Length ft
49 Structure Length ft
50 Sidewalk Rt ft, Lt ft
51 Br Roadway Width (curb-curb) ft
52 Deck Width (out-out) ft
53 Vert Clearance over Deck ft in
54 Underclearance-Vertical ft in
55 -Lateral-Right ft
56 -Left ft
57 Wearing Surface

CONDITION — Material — Condition Analysis — Rating

58 Deck
59 Superstructure
60 Substructure
61 Channel & Channel Protection
62 Culvert & Retaining Walls
63 Estimated Remaining Life
64 Operating Rating
65 Approach Roadway Condition
66 Inventory Rating

APPRAISAL — Deficiencies — Rating

67 Structure Adequacy
68 Deck Geometry
69 Underclearances-Vertical & Lateral
70 Safe Load Capacity
71 Waterway Adequacy
72 Approach Roadway Alignment

PROPOSED IMPROVEMENTS

73 Year Needed Completed Describe (Item 75)
74 Type of Service
75 Type of Work
76 Improvement Length ft
77 Design Loading
78 Roadway Width ft.
79 Number of Lanes
80 ADT 81 Year
82 Prop. Rdwy Improvement-Year
83 -Type

COST OF IMPROVEMENTS

84 Total Cost $,000
85 Preliminary Engineering Cost
86 Demolition Cost
87 Substructure Cost
88 Superstructure Cost

Remarks

Figure 3. SI&A sheet.

Operating Rating

Item 64 is the capacity rating of the structure to the absolute maximum permissible load level to which the structure may be subjected. The capacity to be recorded is the lesser of the deck, superstructure, or substructure ratings. The code used represents the truck type used in the analysis and the total tonnage of the truck.

Substructure Condition Rating

Item 60, Substructure Condition Rating, is a code, from zero to 9, representing the condition of the piers, abutments, piles, fenders, and footing scour. The code is selected by referring to condition statements given in the Coding Guide.

ASSESSMENT OF DEFICIENCIES

Urgency of Corrective Action

SI&A Condition Rating

None of the state personnel interviewed favored using Item 60 condition statements as a method to assess deficiencies and prioritize maintenance projects. This is not surprising because the SI&A condition statements were developed to establish priorities for rehabilitation or replacement projects. Major maintenance, minor rehabilitation, and similarly worded definitions have little significance to maintenance engineers. These statements reflect increasing expenditure levels for needed repairs.

Findings show that although maintenance engineers are far more concerned with the urgency of corrective actions, current guidelines are of little help in setting priorities. Major maintenance can usually be performed within a year, while even minor rehabilitation may have to be scheduled several years in advance in order to acquire or even program the necessary funds.

The amount of money required may also be unrelated to the degree of urgency. An example of this point is the repair of scour or replacement of a defective pile. These are considered maintenance items of the utmost importance under some conditions, but neither of these examples would be considered "rehabilitation."

The example also exists where one pile of one pier in a mile-long structure has underwater deterioration and may cause the bridge to collapse. In this case, the Overall Structure Adequacy Appraisal would be high while the inventory and operating ratings would be low. The low ratings would, in turn, lower the sufficiency rating but not to the point where the structure would qualify for federal rehabilitation-replacement funds. This condition would be viewed as a maintenance project.

Maintenance Urgency Index

In order to prioritize maintenance projects based on the assessment of deficiencies and the urgency of corrective actions, the research team proposed the Maintenance Urgency Index. Figure 4 compares the SI&A condition statements to the Maintenance Urgency Index. A condition level of 9 under the FHWA's SI&A rating guidelines is "new condition"; however, because the description is not indicative of its condition, this was changed to "No Repairs Needed."

The next level of urgency, 8, is essentially the same except that a list of specific items should be made for closer inspection on the next regular inspection. For urgency level 7, deterioration has been noted; however, there are still no immediate plans for repair. At this level, an increase in inspection frequency may be deemed necessary. At level 6, repairs become necessary and should be scheduled by the end of the following season.

When the structure deteriorates to level 5, the urgency of corrective action increases to the point where the repairs must be placed in the current schedule. The structure should be repaired at the first reasonable opportunity. At level 4, the repairs become a priority item. In this case, the maintenance engineer should review the work plan to determine its relative priority and adjust the schedule if possible. In any case, the repairs must be carried out during the current season.

At level 3, the repair is given high priority and the work should be scheduled as soon as possible. If deterioration reaches level 2, the repairs should be given highest priority. If required, other work should be discontinued. Other actions such as traffic restrictions may be considered.

The structure should be closed when the level of urgency reaches level 1. Emergency actions are required and traffic must be rerouted. If the facility is closed for repairs, the structure should be rated as a zero.

PROPOSED GUIDELINE BOOKLET

Appendix G contains the Proposed Guideline Booklet which summarizes the method of arriving at the Maintenance Urgency Index. The booklet is intended to be an independent document that may be carried into the field and used by inspection personnel. It contains a number of guidelines describing several types of substructure elements in various stages of deterioration. These guidelines can be used to select an initial assessment of a deficiency which, in turn, may be modified to determine the Maintenance Urgency Index. The booklet includes instruction for its use in assessing underwater deficiencies.

Proposed Guidelines

Of the states surveyed, only a few have developed their own guidelines to help their inspection personnel in assessing deficiencies for SI&A Item 60. Most states simply use the FHWA bridge inspection training course to standardize their engineering judgment. As a result of the low level of information found, the research team developed its own guidelines for assessing deficiencies. Appendix G contains the guidelines that were developed. These guidelines were reviewed with state personnel during the field visits.

In general, certain common views become apparent. Scour of piles, either

Maintenance Urgency Index	SI&A Item 60 Ratings Based on Maintenance Rehabilitation Level *	Maintenance Urgency Definitions Based on Perceived Immediacy of Action
9	New Condition	No repairs needed.
8	Good Condition	No repairs needed. List specific items for special inspection during next regular inspection.
7	Minor Maintenance	No immediate plans for repair. Examine possibility of increased level of inspection.
6	Major Maintenance	By end of next season - add to scheduled work.
5	Minor Rehabilitation	Place in current schedule - current season - first reasonable opportunity.
4	Major Rehabilitation	Priority - current season - review work plan for relative priority - adjust schedule if possible.
3	Immediate Rehabilitation	High priority - current season as soon as can be scheduled.
2	Urgent Rehabilitation	Highest priority - discontinue other work if required - emergency basis or emergency subsidiary actions if needed (post, one lane traffic, no trucks, reduced speed, etc.)
1	Facility Should be Closed	Emergency actions required - reroute traffic and close.
0	Facility is Closed	Facility is closed for repairs.

*Paraphrased from FHWA SI&A (1978) page 27.

Figure 4. Urgency of corrective action--alternate definitions.

in a bent or under an exposed footing, is of little concern to states with respect to structures in salt water. The exception is untreated timber piling under footings that are then vulnerable to borer attack. States consider scour of pile footings in fresh water to be critical because of the abrasive action of some fast flowing streambed materials.

All states interviewed regarded the exposure of a footing not on piles to be a critical condition requiring immediate attention. The loss of lateral support on a pier shaft, however, was not considered critical by any state unless the spread footing was exposed as well.

Section loss of a concrete pile becomes critical when a reinforcing bar is completely exposed. Section loss on the inside of a timber pile is critical and requires immediate replacement in warm salt water because of the action of marine borers.

Specific comments from the states concerning the proposed guidelines are given below. The reader should refer to Appendix G before continuing.

Scour Around Piles

When evaluating scour around piles, the major concerns are scour resistance of the streambed and pile penetration. In all but a few states visited, light scour is of no concern, requiring no riprap, because of the minimum length of pile needed to meet specifications. In those states where the greatest lengths are required, the bridge maintenance engineers believe that a substantial amount of scour will not endanger the structure. In states with particularly scourable streambeds, any scour problem is considered serious because of possible abrasion damage.

Undermining of Footing

Two parameters that should be considered for a pile footing are type of water (salt or fresh) and type of pile (timber, steel, or concrete). Borers and corrosion are the two main concerns in salt water. In fresh water, however, abrasion of piles due to granular soils is a factor. Actually, when scour of a footing exposes a pile, the pile should be rated separately.

Several states felt that the suggested guideline was too liberal, thereby giving the condition as described therein a lower rating. One state considers load capacity to be a more important criterion than the percentage and depth of piles exposed.

All states visited regarded any scour of a spread footing critical and subject to repair as soon as possible. Scour resistance of the streambed material is a factor that should be considered, with more attention given to material that can erode rapidly. A majority of the states visited felt that a rating system was almost superfluous and would give any amount of undermining a rating that would indicate that repairs were needed immediately.

A distinction needs to be made between scour near a bridge site and scour around and affecting the substructure. Scour of the stream channel should be considered as part of the stream channel condition rating.

Section Loss of Concrete Pile

All states visited agree with the guidelines with only minor alterations. Most states believed that if the main reinforcing bars are completely exposed, the rating should be a 3, but one felt that a rating of 4 would apply.

Section Loss of Steel Pile

With some minor differences in boundaries between ratings (less than ± 10 percent), all states agreed with those values listed. One state, however, would qualify its ratings by the amount of stress induced in the pile due to the given amount of section loss.

Section Loss of Timber Pile

An important factor here is whether the decay is internal or external. Internal decay, rather than external decay, would more than likely be due to borer activity in salt water. Two states said they would replace internally decayed piles immediately, while one would closely monitor the situation.

A majority of the states visited generally agree with the percent loss of areas suggested in the guidelines, with only minor differences. One does not consider section loss because all of their timber structures are being replaced, and another bases its rating on the capacity of the member to carry traffic.

General Deterioration of Concrete

All states visited generally agree with the guidelines. Although, two believed the guidelines to be slightly conservative, a majority agreed that for a 3 to be given, a main rebar should be exposed, free standing, and probably have section loss. One suggestion was that the guidelines could be slightly refined by adding percent areas of deterioration.

General Deterioration of Timber

Half the states interviewed agree with the suggested guidelines, although several would like a distinction made between cracking, which is age induced, and splitting, which is stress induced. Several are more concerned with borers entering through checks, and if those checks go to the heartwood. These states would simply replace that member. One state is more interested in the function of the member as opposed to its general condition.

Settlement

There was relatively little agreement with the proposed guidelines concerning settlement because there was more concern with the ability of the bridge to function and carry traffic. Ridability and the ability of the bearings to contract or expand are important. One state considered a 3/8 in. settlement of a simple span pier to be serious and cause for a complete study of the situation, while another thought that most dimensions that were given in the guidelines should be halved.

Several states had difficulty distinguishing between minor and moderate tilt in a member. Two other states would require an analysis at a rating of 4 or 5.

Guideline Booklet Use

Initial Assessment

Each deficiency of a structure must be assessed independently. Inspection personnel must observe a particular deficiency, compare it to the guideline provided in Appendix G, and select the description that most closely depicts the severest example of deterioration found. The number appearing adjacent to the chosen description is the initial assessment.

Assessment Modification System

It was found that there were inconsistencies between states as to how various deficiencies should be assessed. At the beginning of the study, the inconsistencies were thought to be arbitrary, but after additional research and closer observation, it was discovered that true differences do exist between and within states. These differences led to the development of an assessment modification system. The purpose of the modification system is to account for variations in the primary factors influencing deterioration.

The modification system consists of a set of numerical values assigned to various conditions. The values range from

Modification	Description
+2	No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect.* (Note: May be used for original rating of 2 to 6 inclusive.)
+1	No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect.* (Note: May be used for original rating of 2 to 7 inclusive.)
0	No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)
-1	Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)
-2	Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)

* Structural effect includes redundancy of load path and other factors.

Figure 5. Modification chart based on threat to integrity of structure.

+2 to -2. The modifications are shown in Figure 5 . The appropriate modification is chosen on the basis of how long it will be before the deficiency is a threat to the structure. The modification is selected after a review of the history of the site, the environment, and future land use for the region.

The administrative level at which the assessment modification is approved is not addressed here. It is conceivable that a modification may be suggested by the inspector and then approved by others.

The history of the site is significant because it helps the inspector determine whether conditions have remained the same or if they are changing. It helps him determine what deficiencies require closer observation. Defects resulting from settlement, such as cracking, may be exacerbated if the structure is located in an active seismic area.

The environment must be considered to determine various parameters. Rainfall and streambed materials are significant in assessing abrasion and scour. Knowledge of the chemical environment is needed to estimate the expected rates of corrosion and chemical attack. The temperature fluctuation will indicate whether freeze-thaw is a factor.

Bridge orientation or surroundings may create a condition where timber piles in the splash zone are never exposed to the sun, remaining constantly moist and causing accelerated decay.

Future land use for the area is significant. Clearing of land would affect runoff, a dam would affect stream flow characteristics, and an industrial plant upstream from the structure could affect the chemical environment in the water increasing deterioration.

One example that highlights the inconsistency which can arise when assessing a deficiency is the case of exposed piles under a footing. These piles might be subjected to totally different environments depending on geographical location. Photographs from different locales showing identical degrees of deterioration will look the same. However, to an engineer in a coastal region, exposed timber piles could be subjected to marine borers; whereas this would be of no concern to an engineer in a freshwater area. On the other hand, the same piles in fresh water would be more subject to abrasion and scour because of fast moving water, while in coastal regions scour pockets may simply fill back in during the next season.

An actual example of how the environment can have an effect on the seriousness of a particular problem is the Wareham Narrows Bridge on U.S. Route 6 in Massachusetts. The bridge is of particular interest because recently an electrical crossing signal was installed on a railroad bridge close by. Shortly after installation, the Wareham Narrows Bridge began experiencing abnormally high corrosion rates believed to be caused by stray currents coming from the crossing signal. In this case, corrosion would present a much more serious problem to the inspector because of its high rate than it would if the signal was removed and corrosion would stabilize.

One final example of the effect of geographic location is that of the effect of terrain, which is most dramatic in mountainous regions. A bridge on the windward side of a large mountain would more likely receive more rain and, consequently, more runoff, than a bridge only a few miles away on the lee side.

Maintenance Urgency Index

Once all the parameters have been considered, the inspector must then select the appropriate modification. By algebraically adding the initial assessment and the modification together, the inspector can arrive at the maintenance urgency index. It is intended that this index will more accurately depict the urgency of corrective action, relating to how local conditions affect the rate of deterioration. The index does not imply that if two structures are numerically the same, that the structures are in the same specific condition. It means that the urgency of repair is the same for both structures.

Once the maintenance index has been established, three modes of action are indicated. For levels 6 through 9, the inspector need only note the deficiency in the inspection report. For levels 3 through 5, a structural capacity analysis is necessary. For levels 1 and 2, the inspector should notify the appropriate personnel immediately, either by telephone or in person. If required, traffic restrictions should be imposed and repairs undertaken immediately. Traffic restrictions include: posting a weight limit on the structure, reducing the number of traffic lanes, or reducing the speed limit. The flow chart in Figure 6 outlines this process.

EVALUATION OF DEFICIENCIES

The following techniques for evaluating deficiencies were assessed for ease and speed of application, destructiveness, underwater usefulness, provision of quantitative strength measurements, and cost effectiveness.

Inspection Techniques For Concrete

Various methods are presently in use or currently under development for the evaluation of concrete under water. A summary of these test methods is presented in the following.

Visual Assessment

Visual assessment is invariably the first test that is applied. It is quick, easy, and nondestructive; however, it has had only limited success under water because water turbidity, i.e. poor visibility, affects the result. Additionally, it is only qualitative in nature and does not provide a direct measure of strength.

Physical Dimensions Measurements

The measurement of physical dimensions provides direct information about section loss of concrete and reinforcing steel. This method is quick and easy, results are quantitative, and it is economical even under water because of the minimal amount of time and equipment involved. The method is nondestructive, is applicable to underwater use, and provides a partial measure of the member's strength. Its primary drawback is that it does not provide information on the strength of the remaining concrete which is generally in question at this well-advanced stage of deterioration.

Soundings

Soundings are taken by striking the concrete surface to locate areas of delamination of the concrete cover caused by the effects of freezing and thawing and corrosion of the reinforcement. The method is economical but not particularly effective because it is only qualitative in nature and the inspector's ability to hear sound in water is reduced by waves, currents, and background noise.

Cores

Cores are taken under water to provide a cross section of the concrete. Cores permit petrographic analysis and other laboratory procedures that measure compressive strength, diffusion constant, permeability, electrical resistivity, density, x-ray diffraction, moisture content, chloride penetration, extent of carbonation, and air entrainment.

The technique requires a coring drill equipped for underwater use and a materials laboratory. The method is destructive in that it causes microcracks and leaves holes. Coring gives a direct measure of strength, but because it is moderately expensive, cores are typically taken only when other evidence indicates that further investigation is warranted.

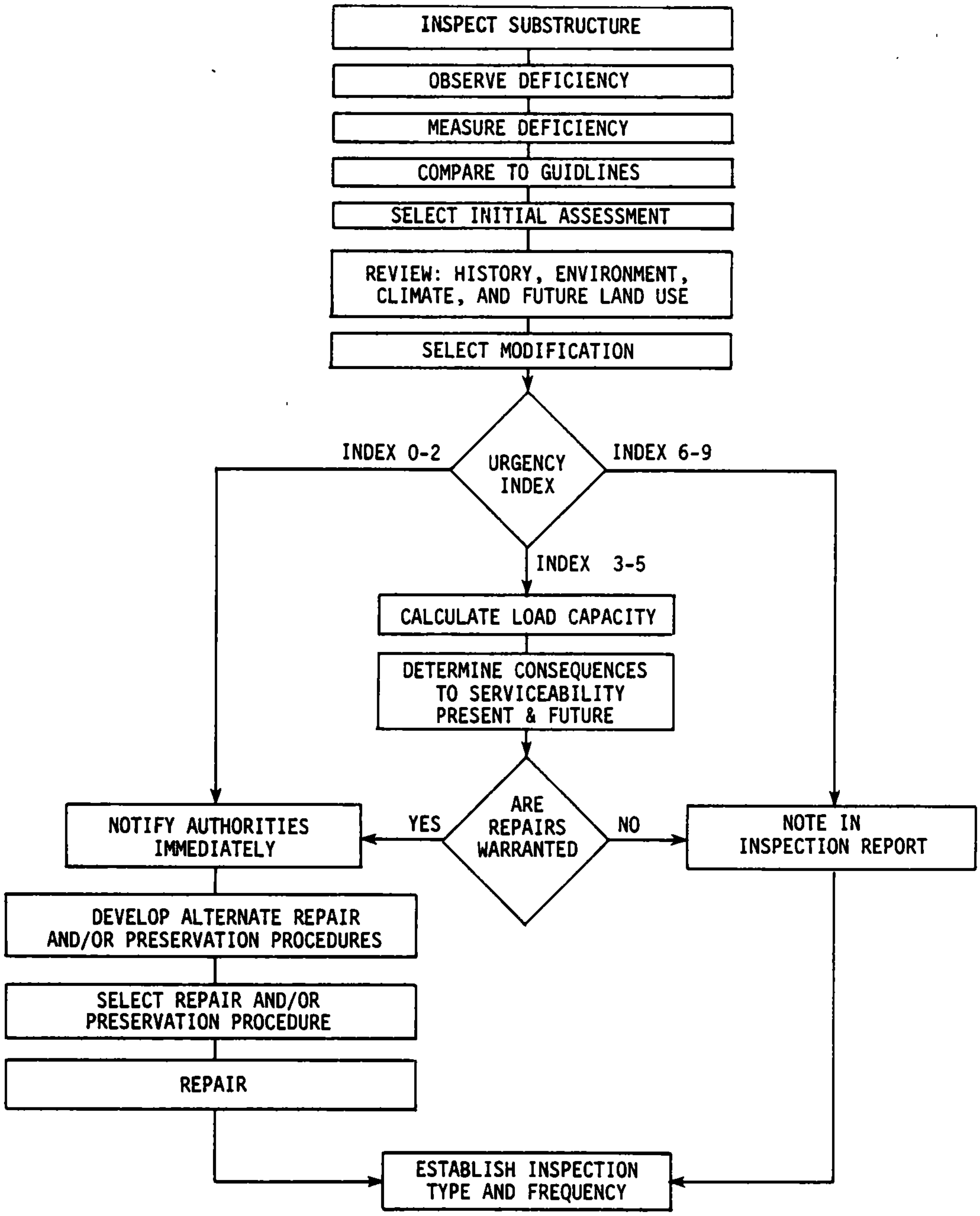


Figure 6. Flow chart outlining the assessment, evaluation, analysis and maintenance process.

Ultrasonic Pulse Velocity

Ultrasonic pulse velocity measurements are taken under water of the time of transmission of an ultrasonic pulse of energy through a known distance of concrete. The velocity of the pulse is proportional to the dynamic modulus of elasticity, sometimes referred to as hardness, which, in turn, infers concrete strength. The test evaluates homogeneity and determines crack location.

The results can be affected by many factors including aggregate and reinforcing steel location. The results obtained are quantitative, but they are only relative in nature. Results need to be correlated with other tests such as corings, in order to obtain absolute values (2).

Voltage Potential Readings

Voltage potential readings are taken to assess the state of corrosion of the reinforcement by making an electrical connection to the reinforcing steel. Once the connection has been made, the test is easy to perform and is nondestructive. A porous tip electrode connected to a high impedance voltmeter is placed directly on the concrete surface over the reinforcing steel and a comparison is then made of the potential between the steel and a standard reference electrode, usually silver-silver nitrate under water and copper-copper sulfate in the splash zone.

The most satisfactory results are obtained when the readings are used in conjunction with a chloride penetration analysis of a core test. The readings indicate whether or not corrosion is active and the extent of the concrete surface area involved. However, it gives neither the rate nor the amount of corrosion. No indication of strength is provided.

Computer-Assisted Tomography

Computer-assisted tomography (CAT) scanning uses a nuclear source to develop a cross sectional view of a member. It yields information on the size and location of aggregate, cracks, and voids; density; and extent of corrosion (3). This method is nondestructive and can scan members up to 3 ft thick. The method is very expensive, gives no direct measure of strength, and poses a potential health risk to the user. Its underwater application is presently experimental and is under development in the United Kingdom (2) and at the University of Texas.

Polarization Resistance Measurements

Polarization resistance measurements can actually measure the rate of corrosion. Several techniques are possible to apply this technology. The best candidates are the AC impedance, two-electrode, and three-electrode methods. The AC impedance method has not been pursued in research because of potential equipment problems in field use. The two-electrode method applies a 20 mV potential between the electrodes, one being the rebar that is being measured. The current necessary to produce the change is noted and the polarity is then reversed to allow the average current to be determined. This method suffers from several problems, however.

The three-electrode method shows the best reliability. One electrode is the rebar whose corrosion rate is being measured. The second electrode serves as a source of current during polarization, and the third electrode is a standard reference to which measurements are made. The normal potential of the steel is modified by an external current similar to the two-electrode method. The resulting voltage and current give an indication of the rate of corrosion.

Various methods to analyze the resulting data include: slope of the polarization curve near zero current method, three-point method, graphic analysis, and "break in the curve" method. The test is nondestructive except for an electrical connection to the reinforcing steel. This technique has not been developed for underwater testing thus far and is still under research for field testing in-the-dry (4).

Other Methods

Other methods were revealed in the literature search that have not been developed for underwater use but conceivably may be in the future. These tests are the:

- Pull-out test (5, 6).
- Penetration test (7).
- Indentation test.
- Resonance test.

At present, the states surveyed use only cores, sounding, physical dimensions, visual assessments, and engineering judgment to arrive at values for reduced allowable stresses and cross sectional area. These tests are likely to reveal trouble only after the deterioration process is well under way and substantial damage has already occurred. The best results are most likely to be obtained from a combination of several different tests with a large number of samples because of the wide variation in results that can be expected due to the nonhomogeneous nature of concrete.

As a rule, destructive testing should be avoided. Any test that induces cracks or reduces concrete cover can only encourage deterioration. However, if after testing, all holes are filled and all cracks are sealed, the deleterious effects of testing can be minimized. This care should be applied to all materials.

Inspection Techniques for Steel

Various methods are in use or are currently under development for evaluating steel under water. The leader in this field is the maritime industry. Because putting very large, crude-carrying (VLCC) ships in dry dock is prohibitively expensive, the underwater inspection of VLCC ships has become a necessity. Although the test procedures may be expensive because of the size of their operations the procedures can become cost effective.

Special consideration should be given to the cleaning of steel surfaces to bare metal which is required for some of these tests. Visual inspection should be made before cleaning because a change in color of marine growth can indicate a crack. Additionally, cleaning should be avoided in the case of dense marine growth or greenish-black rust both of which provide a dense covering inhibiting further corrosion.

Most of the tests (8) presented below are to detect cracks in welds. Some of these procedures could find limited use in bridge engineering.

Visual Assessment

Visual assessment is only qualitative in nature and does not provide a direct measure of strength.

Physical Dimension Measurements

The measurement of physical dimensions provides necessary information required in analyzing the structure.

Soundings

Sounding bolts and rivets method can only be effectively used under water in low noise areas.

Coupon Samples

Coupon samples are taken under water for laboratory analysis, but this procedure is destructive and is generally only done if other evidence indicates that this is warranted.

Ultrasonic Testing

Ultrasonic testing will locate cracks. This nondestructive test uses a hand-held transducer below the water surface combined with a meter above the surface. Water acts as the coupler so grease is not necessary to ensure contact. The procedure is slow and difficult to use because the diver cannot see the read-out unless he has a display in his helmet. Reflection at the steel-water interface is not as efficient as at a steel-air interface.

This device has been used to measure member thickness even though pitting of the surface will scatter the signal. A transducer on a long cord also tends to reduce its efficiency.

Magnetic Particle Testing

Magnetic particle testing will locate surface cracks in steel with an induced magnetic field. The particles are fluorescent and suspended in slurry in a squeeze bottle for underwater use. The method is quick and economical although limited because only surface defects are located.

Radiographic Inspection

Radiographic inspection locates cracks under water by using a film cassette with an x-ray or gamma ray source placed on opposite sides of a weld. It produces a permanent record of the crack. It is expensive, hard to use, and poses a health risk to the diver unless extreme caution is exercised.

Acoustic Holography

Acoustic holography locates cracks under water using an array of ultrasonic transducers to produce a multidimensional picture and a permanent record, but the test is expensive.

Inspection Techniques For Timber

One of the oldest building materials is wood. Experience in the deterioration of timber dates from antiquity. Even so, various methods are under development to evaluate timber under water, while others are in current use. These are the following.

Visual Assessment

Visual assessment, as before, is only qualitative in nature.

Physical Dimension Measurements

The measurement of physical dimensions is only applicable in areas of low noise.

Soundings

Sounding with a hammer will detect voids and can be used to subjectively estimate the quality of existing timber. This method can only be effectively used under water in low noise areas.

Pointed Probe

Resistance to a pointed probe is another method to subjectively estimate the quality of existing timber.

Surface Probe

Probing of the surface, drilling several inches into the timber and probing again, is a procedure that aids in the separate assessment of surface and interior conditions.

Brace and Bit

Brace and bit will yield qualitative results by noting the resistance to advancement of the bit and residue on the bit upon withdrawal. Resistance may change, however, because of the internal structure of the wood and not decay. Also, residue may shift along the bit, also distorting the results. The method does not provide a measure of strength.

Bores

Increment bores produce undisturbed continuous samples, but the results are qualitative. This method is slightly destructive and does not measure strength.

Figure 7. Internal decay of timber pile.

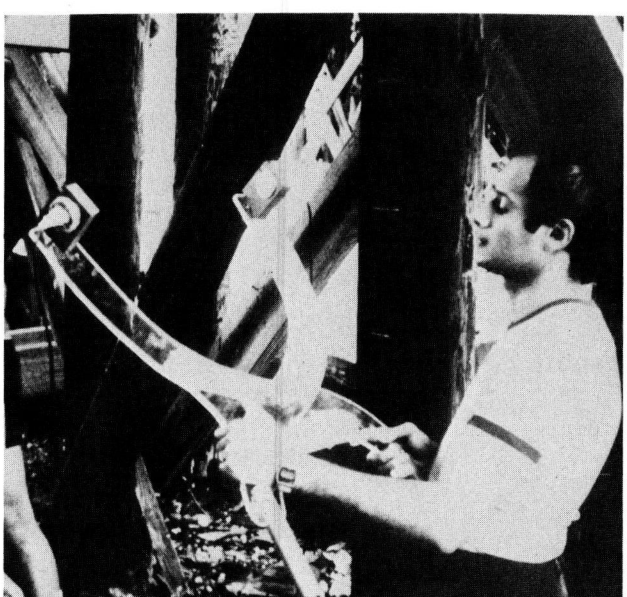


Figure 8. Sonic testing device.

Sonic Pulse Velocity Testing

Sonic pulse velocity testing indicates relative timber strength and/or section loss as a single value based on a transmitted pulse velocity that is proportional to density and the modulus of elasticity. Correlation of results with samples of known strength is required in order to arrive at an absolute value. Research has been under way for about 20 years. Several commercial diver-operated devices are on the market, and a number of contractors also offer underwater inspection services using this technique.

M. Sharif Aggour of the University of Maryland leads a research team that is developing a hand-held device that will be operational from a boat to a depth of 1 m below the waterline. They have built up a data base of 50 points. Figures 7 and 8 show this device.

Other Methods

Other methods were identified in the literature search that have not been developed for underwater use, although they may hold promise for such use in the future. These tests are:

- CAT scan (9).
- Electrical resistance test (10).
- Sonic pulse frequency test (11).
- pH test (10, pp 22-23).

At present, states surveyed are using borings, brace and bit, pointed probe, sonic testing, soundings, and engineering judgment to arrive at a value for reduced stress.

STRUCTURAL CAPACITY ANALYSIS

A great body of work exists on the deterioration of materials used for substructure construction and its causes, but relatively little information is available concerning the consequences of such deterioration to the structural integrity of substructure units. Because of the necessity of rating structures under the federally mandated bridge inspection program, state highway agencies have evaluated the consequences of deterioration, but it is largely "engineering judgment" in nature.

Current Practice

Only a few states always analyze substructure units. Most states analyze substructure units when it appears warranted by a deficiency, but other states simply repair the deficiency and do not perform an analysis. None of the states surveyed have developed novel methods for the structural analysis of bridge substructures above or below the waterline. Reduced stress and cross-section area are incorporated into commonly accepted stress analysis computations. In arriving at these values, no state surveyed has developed methods that are considered unique to measure the adequacy of concrete, steel, or timber.

Settlement

None of the states surveyed analyze a substructure unit for settlement when it occurs. Shimming is the corrective action selected because it is an inexpensive and relatively easy process. Uniform settlement of all the substructure units of a bridge will not usually induce overstress. Modest differential settlement of a simple span structure will likewise create no distress. If settlement is deemed significant, steps are usually taken to determine the cause. Computations can be performed on a continuous span superstructure to determine stresses induced due to differential settlement. Here again, analysis of the substructure is not performed. All states interviewed agree that it is not the settlement itself that is the crucial factor, but rather it is the distress that settlement causes to the structure as a whole.

Scour

Scour of foundation material from beneath spread footings is evaluated for stability by few states. The action most often taken is not to analyze the deficiency but rather to repair it. In Maryland, once scour of a spread footing is discovered, it takes highest priority. If necessary, all other activities by the maintenance crew are suspended and repairs undertaken immediately. Because many bridge failures are caused by scour, their concern is justified. Other states vary in their response, depending on the history of the region and the scourability of the soil. This point will be discussed further in the next section.

Friction

Reduced friction capacity of a pile due to scour is calculated in few states. Reduced lateral support of a pile due to scour is calculated rarely. Again, these deficiencies are normally just repaired.

Proposed Practice

Inspection and analysis of bridge substructures is important, even though many states do not analyze this portion of a structure. The structural members in substructures are just as critical and often less redundant than their superstructure counterparts. An example would be that of a timber bent that may support up to 10 lines of beams, while the bent itself may consist of only three piles. The failure of one pile could be much more critical than the failure of a single beam.

State highway agencies usually analyze a bridge substructure only when a deficiency exists. These agencies believe that there is no need for an analysis when repairs can be promptly accomplished.

What is needed for inspection personnel is to have a quick indication of the severity of a deficiency. Much could be gained if inspection personnel had the ability to determine the severity of deterioration on the load capacity of a structure. Three methods are suggested to answer the need.

Method One

In the first method, specific instances of borderline deterioration would be exemplified. Cases would be delineated such as scour of spread footings and internal decay in salt water. These qualitative discussions might provide inspection personnel with the ability to quickly assess the severity of a deficiency. This assessment should be verified later with a more exact office analysis by an engineer knowledegable in structural and foundation analysis.

Method Two

A second method would be to derive equations for the structural capacity before the inspection is performed. These equations would account for material strength reduction and section loss, and could be used, for example, to analyze deterioration in any pile at any location. The equations would be included as a permanent part of the bridge inspection folder. This method would require an extra effort beforehand, but would save time at the bridge site.

An application of this method would be for the inspection team to carry a programable calculator with analysis programs for several types of common substructure units with them into the field. Programable calculators may prove to be an expensive addition to the bridge inspection paraphernalia. Durability of the calculator in the field may also be a problem.

An alternative to this would be to perform a complete analysis in the office and determine the limits of deterioration for each member. An illustration of the substructure showing the allowable deterioration could then be included in the bridge folder to aid inspection personnel in determining how critical a deficiency is to the serviceability of a structure. A method for displaying this information is shown in Appendix F.

Method Three

A third method also available is to use generalized charts and graphs for the determination of live loads and dead loads. By applying the laws of statics, and following the example in Appendix F, inspection personnel could then determine the structural capacity of the substructure at the bridge site. This method is essentially the same as an office analysis; however, it should again be verified later with a more exact office analysis by an engineer knowledgeable in structural and foundation analysis.

The deterioration of a substructure unit supporting short spans can under certain circumstances be more critical than that of a substructure unit supporting long spans. This is because the ratio of live load to dead load is small in the latter, while it is much larger in the former. Substructures supporting long spans are also designed for larger superstructure forces, i.e. longitudinal forces due to the live load, and larger substructure forces, i.e. stream force and wind. These forces which are included in the original design are ignored in the live load capacity analysis. This gives the substructures of long-span structures a larger capacity than necessary to support dead and live loads. It is for this reason that Appendix F includes an example of an analysis of a timber pile bent supporting short spans that has suffered 1 in. of external decay to one of its piles.

Chapter Three

PRESENT METHODS TO ARREST CONCRETE DETERIORATION

CONCRETE DETERIORATION

The vast amount of information found on concrete deterioration and its causes is testimony to the widespread problem that exists. Research into methods to repair concrete below the waterline is less impressive. This situation can be attributed to financial limitations and to the fact that concrete deterioration of bridge substructures is not in full view of the traveling public. One disturbing observation is that most states defer maintenance until replacing deteriorated concrete becomes the only practical method remaining for an attempt to arrest deterioration.

A majority of the bridge maintenance engineers contacted during the field interviews estimated that 75 to 90 percent of the concrete that is deteriorating under water in their states can be traced to a lack of quality control during construction or to other construction and preconstruction faults. This is because high quality concrete is virtually inert in most natural environments. Appendix C contains detailed information about concrete and concreting practices that can be used for either repairs or new construction.

Zones of Deterioration

Primary Active Zone

One reason for the lack of information on underwater repair techniques is that most deterioration does not occur under water. It has been observed that deterioration occurs most frequently above the level of low tide and below the top of the splash zone. Below the level of lowest water the concentration of oxygen decreases rapidly with depth. Water also has the effect of sealing the concrete from the ingress of oxygen when compared to the atmospheric zone. Above the splash zone there is a lack of water that is necessary to lower the electrical resistivity of the concrete and to provide additional aggressive agents. The zone between these two limits, which includes the tidal zone and the splash zone, is referred to by the research team as the "Primary Active Zone."

Secondary Active Zone

Deterioration at the mud line, whether due to abrasion, reactive soils, or a macrocorrosion cell, also occurs. This area may tentatively be considered as a secondary active zone. If deterioration is confined to the primary active zone, repairs are greatly simplified.

Types of Deterioration

Corrosion

The primary factors influencing the corrosion of reinforcing steel are:

- The presence of chloride ions at the reinforcing steel.
- The decrease in electrical resistivity, or conversely, the increase in electrical conductivity of the concrete cover.
- The availability of oxygen.

The first two of these factors are properties of the concrete cover and the last is a property of its environment.

Interaction of these factors determines the time at which corrosion becomes active, the rate of corrosion, the time at which damage becomes visible and the nature of the damage.

All coastline states surveyed are most concerned with the deleterious effects of salt water. This concern seems to overshadow any difficulties these states are having with their structures in fresh water.

Chemical Attack

Chemical attack is usually a slow process and significant in itself in that it destroys the concrete cover over the reinforcing steel. At this point, corrosion takes over as the dominant force in concrete deterioration. Carbonation, the most prevalent form of chemical attack, was found to progress no further than 1 in. into the concrete surface. This would be of no consequence to nonreinforced concrete.

Interviews revealed somewhat less concern with deterioration caused by industrial waste than was anticipated. Of the states surveyed, two report a problem with paper-mill outfall. Other states report problems with the outfall from a phosphate plant, a sewage treatment plant, a steel mill, and an insecticide plant. Tannic acid, fluoride, logging debris, and mining in basic soils were also reported to be a problem. No state surveyed reported a problem with acid runoff from mining activities. It was explained by the Kentucky Department of Transportation that acid concentrations become diluted before they have a chance to react with bridge substructures.

Abrasion

Abrasion occurs in two zones. Ice fluctuating with the tides can cause section loss at the waterline. At the mud line, sand movement in the surf zone can cause a similar problem. It is suspended solids in fast moving streams, however, that causes the greatest concern.

Freeze-Thaw

Freeze-thaw is a mechanism that is most active at the waterline. The process occurs when the tide drops, exposing wet concrete. The water in the concrete pores then freezes, expands, and creates large internal stresses. When the tide eventually rises, the internal ice melts and the cycle repeats.

Stages of Deterioration

In order to select a method to arrest deterioration, some understanding of the deterioration process that is occurring is necessary. This process has been broken down into three stages: (1) initiation stage, (2) propagation stage, and (3) destruction stage.

Initiation Stage

The initiation stage is where chemical and mechanical forces affect the concrete surface only.

Propagation Stage

In the propagation stage, chemical and mechanical forces affect the concrete cover. In unreinforced concrete this action will simply weaken the outer surface layers. Pre-existing porosity, cracking, and scaling allow aggressive agents to reach the reinforcing steel and begin the corrosion process.

Destruction Stage

The destruction stage is where chemical and mechanical forces have negated the protective qualities of the concrete cover. Corrosion of the reinforcing steel then becomes an accelerating process. In unreinforced concrete this stage is noted by the loss of the outer surface layers of concrete. Appendix D contains detailed information on each stage of deterioration.

Grouping of Repair Techniques

Permitting deterioration to progress to the last stage before repairs are made is not necessary. Many steps can be taken before that point to arrest concrete deterioration. Cores, drillings, voltage potential readings, and/or chemical analyses will be necessary to determine the depth and concentration of chlorides, extent of carbonation (see App. D, carbonic acid, for details), and whether or not corrosion is occurring. These tests are necessary to ascertain the stage of deterioration of the concrete. Once the stage of deterioration is established, a suitable repair method can be selected.

The methods described as follows have been grouped under different stages of deterioration; the groupings represent the most cost-effective technique available to arrest deterioration of concrete at that particular stage:

1. Initation stage.
   - Hydraulic training.
   - Penetrating sealants.
2. Beginning of the propagation stage:
   - Surface coatings.
   - Veneers.
3. End of the propagation stage.
   - Wraps.
   - Jackets.
4. Beginning of the destruction stage:
   - Crack sealing.
   - Sacrificial concrete collar.
   - Grout repair
   - Passive cathodic protection.
   - Active cathodic protection.

REPAIR TECHNIQUES

Hydraulic Training

Abrasion attacks the concrete surface and is a major force in the initiation stage. Abrasion also aggravates other forms of deterioration throughout the life of a structure. Hydraulic training structures are of some help in arresting abrasion. The methods include the following:

Deflectors

Fenders and dolphins arrest abrasion at the waterline. They can be efficient, and are able to absorb a large amount of energy. This method can be expensive, however, requiring heavy machinery to drive piles and a moderate amount of construction time.

Riprap

Probably is the least expensive method where abrasion concern is only at the mudline. However, cost is dependent on location since suitable stone is not always readily available.

Ponding

Ponding of the water beneath a bridge is quite effective in arresting abrasion by reducing the water velocity. This is accomplished by means of a downstream dam, by mangement pond, or by widening the stream. This method is expensive, requiring labor, heavy machinery, rights-of-way, and construction time. It has limited application because of topography, because of permit requirements, and because the procedure is self-defeating in some cases. As water velocity decreases, the stream will deposit its suspended solids, silting the pond back in, and alter the hydraulic flow beneath the structure. Figure 9 shows an island that was created by deposition when a river was widened.

Other Training Structures

Spurs, dikes, jetties, and channelization can be used to direct flood waters away from piers. This method is moderately expensive and will require environmental and 404 permits.

Penetrating Sealants

Much experience has been gained in the field of concrete pipe linings and bridge deck membranes; however, no *in situ* underwater application was found for any of the penetrating sealants listed below. The sealants listed are not elaborated upon because they cannot currently be placed under water.

Inorganic surface sealants include the following synthetic compounds (12):

1. Coatings which react with calcium in the concrete to form practically insoluable compounds; their resistance is fair to chemicals in general but poor against strong acids:
   - Hydrofluoric acid or its salt.
   - Hydrosilicofluoric acid or its salt.
   - Magnesium fluosilicate.
   - Zinc fluosilicate.

2. Vapor permeable coatings:
   - Acrylic latex paints.
   - Cement base paints.
   - Cement mortar coats.
   - Polymer-modified cement mortar.
   - Water-base epoxy paints.
   - Silicone resin solutions.
   - Mineral oils in solvents.

Surface Coatings

The main purpose of a coating is to prevent physical and chemical contact between the concrete and its environment. By sealing the surface, the ingress of chemicals, especially oxygen, can be stopped thereby helping to arrest deterioration. Resistance to abrasion, chemical attack, and the effects of freezing and thawing are desirable characteristics.

The coating should have an adhesion strength greater than the tensile strength of concrete, a coefficient of expansion that is compatible with concrete, and a long service life; it should also be economical. Its viscosity should be selected so that it will provide maximum sealing of the surface, considering the porosity and texture of the concrete. It should be elastic and should not creep. If aesthetics are important, the color and texture of the sealant should have a matching appearance with the concrete surface.

Figure 9. Island created by ponding.

Surface preparation is very important to the success of sealants and coatings. Most sealants and coatings do not perform well when applied to concrete under water. However, if water could be pumped from within a dewatering form, these materials could be applied "in-the-dry." Several portable cofferdams were discovered during the literature search (14, 15). One of these is large enough to allow a man to work inside of it.

Three problems exist when trying to seal the surface of damp concrete. First, good bond is hard to attain. Second, no matter how thoroughly the concrete is dried, if it is permeable, it will become saturated again due to the wick action of partially submerged concrete (Wick action is the process in which water and chemicals are drawn in at the bottom of a surface coating or treatment and water vapor is expelled from the top leaving a high concentration of chemicals under the concrete surface.) Third, encapsulating concrete that is, or that will become, damp is a poor practice because the sealant is more likely to pop off in direct sunlight due to increased vapor pressure. Vapor-permeable coatings that claim to keep water out while permitting vapors to escape can solve this problem (15). These coatings include (17):

- Acrylic latex paints
- Cement base paints
- Cement mortar coats
- Polymer modified cement mortar
- Water-base epoxy paints
- Silicone resin water repellant solutions
- Mineral oils in solvents

Surface coatings suitable for underwater use include those listed below. There are multitudes of others, however, whose underwater application is doubtful.

Asphalt and Tar

Asphalt and tar were widely used at one time. Asphalt has a high resistance to acids and oxidants. It can be applied cold with the use of a solvent. Tar is the sealant most often used against seawater attack. It is an excellent water repellant, but it is mediocre against acids and bases and poor against abrasion. For both of these bituminous products, the second coat may contain a filler such as silica for stiffness. Strict quality control is necessary to ensure a continuous coat.

Epoxies

Epoxies have many advantages. They have good adhesion, low shrinkage, a wide range of physical and chemical properties, and a very high compressive strength. They attain a high early strength, are inert to most chemicals, and are moisture resistant. They are impervious and both abrasion and chemical resistant. They may be applied with a roller or brush.

Epoxies were thought to have almost unlimited application when they were first introduced. Use under field conditions over the years, however, has not provided satisfactory results in many instances. Figure 10 shows a typical epoxy failure. Mixing requirements are exacting and components are hazardous to the users. The mix has a short pot life and is heat sensitive during mixing and application. Strain incompatibility results from rapid hardening and a thermal coefficient of expansion that differs from that of concrete.

Epoxies creep, relax, and are impact sensitive. Physical and chemical properties are very selective, varying between manufacturers and between environments. Field tests should be conducted to determine the performance of an epoxy brand and mix. Because epoxy is impermeable, moisture trapped beneath the coating may cause it to spall off in direct sunlight or under the effects of freezing and thawing. Epoxy should not be used unless the concrete can resist frost action by itself. It is expensive and as a result tends to be economical for small jobs only.

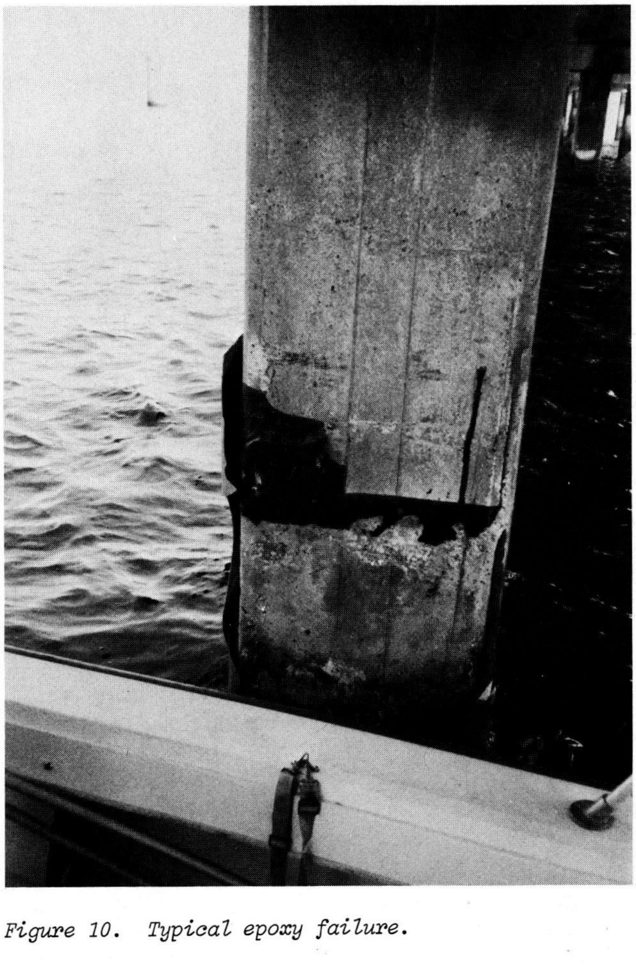


Figure 10. Typical epoxy failure.

Tar Epoxy

Tar epoxy is a low ratio mixture of polymerized tar and epoxy. It was developed as a lower cost alternative to epoxy (13).

Epoxy Polysulfide

Epoxy polysulfide is resistant to solvents and has improved impact resistance (13).

Other Surface Coatings

Other surface coatings that are used for concrete pipe linings but have not been applied to underwater deterioration of bridge substructures (13) are:

- Polyvinyl chloride
- Polyethylene
- Styrene copolymers
- Chlorinated rubber
- Neoprene
- Coumarone - indene
- Phenoplastic - furnace resin
- Polyurethane
- Polyester
- Chromated rubber paint
- Bituminous mastic
- Asphalt mastic
- Proprietary rubber compounds.
- Dried oil
  - Tung oil
  - Linseed oil
- Sodium silicate
- Resins
  - Spar
  - China wood
  - Bakelite

Veneers

In case of extreme chemical attack, facings can be applied to the concrete surface. Bricks and tiles of clay, glass, or carbon are usually 230 x 115 x 75 (or 50) mm in size. Kilned at high temperatures, these semivitrified facings are very dense with low water absorption. The bricks and tiles are joined to the concrete with a chemically inert mortar.

Three types of mortar are available. (1) synthetic thermo-setting cements consist of resins of phenol, furnace blast, epoxy, cashew, polyester, and polyurethane. (2) potassium silicone cement suitable for acid conditions performs poorly in alkaline and fresh waters; and (3) for less corrosive environments, modified hydraulic cements, such as natural rubber latex and synthetic resin emulsion, may be used (18).

Wraps

Plastic and Rubber Sheets

Plastic and rubber sheets are good for severe chemical attack and most can be vulcanized. Types include: neoprene, butyl, nitrile, polyisobutalene, polysulfide, and chlorosulfonated polyethylene. These wraps sometimes have vertical wooden ribs that are interlocked and drawn tight around the pile or column with a ratchet wrench. A metal clamp can provide a seal at the top and bottom of the pile to insulate it from its environment.

The rationale for this process is that residual oxygen trapped within the wrap will be consumed and deterioration will be arrested. This system is very quick and inexpensive; however, it offers little resistance to impact and can only be used on relatively smooth surfaces (18). An example is shown in Figure 11.

Resin-Impregnated Fiberglass Cloth

Resin impregnated fiberglass cloth wrap is placed around a pile or column and soaked with brushed-on epoxy. This method is quick and lightweight but costly and difficult to use.

Jackets

There are several types of jackets that have been used.

Fabric

Fabric jackets offer low labor and materials cost with a minimal installation time. An example is shown in Figure 12. The jacket is assembled above the waterline and then clamped around the pile or column at the bottom and filled with concrete. Bleeding of mix water through the fabric results in a denser mix.

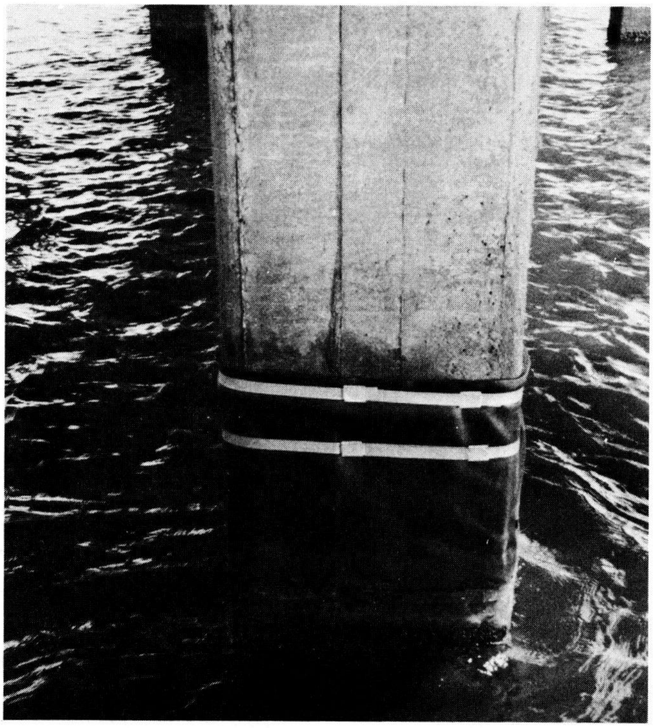


Figure 11. PVC pile wrap (note metal bands).

Figure 12. Fabric pile jacket, concrete filled. Ropes used to suspend jacket during construction were left in place.

This method is quick and easy; however, the jacket can deform in currents and waves, reducing the cover over the reinforcing steel cage that is placed around the pile inside the jacket. Aesthetics are also compromised when the bag deforms. A concrete sample is hard to obtain because of *in situ* bleeding.

Nonmetallic

Nonmetallic Jackets, usually fiberglass, consist of a one-piece or a two-piece semirigid unit that may bolt or interlock at the seam(s). These forms can be removed or left in place for added protection. They can be filled from the top or with a valve from the bottom with either epoxy, epoxy mortar, or concrete, and if the forms are left in place, they can be sealed at the top and/or the bottom with a layer of epoxy.

Nonmetallic jackets are lightweight and easily handled in the water by a diver. Their rigidity makes them more desirable than fabric pile jackets for some applications. Fiberglass jackets have been observed, in some cases, to have a tendency to separate from the grout filler material and even to become dislodged. Figures 13 through 17 show these jackets in service.

Steel Jackets

Steel jackets and metal collars are sometimes used. They come in many sizes, up to several feet in diameter. They can be filled from the top or the bottom with either epoxy mortar or cement mortar with epoxy bottom and top seals. These jackets

Figure 13. Fiberglass jacket filled with epoxy.

Figure 14. Fiberglass jacket filled with epoxy grout.

Figure 15. Fiberglass jacket filled with epoxy grout (note failure in background).

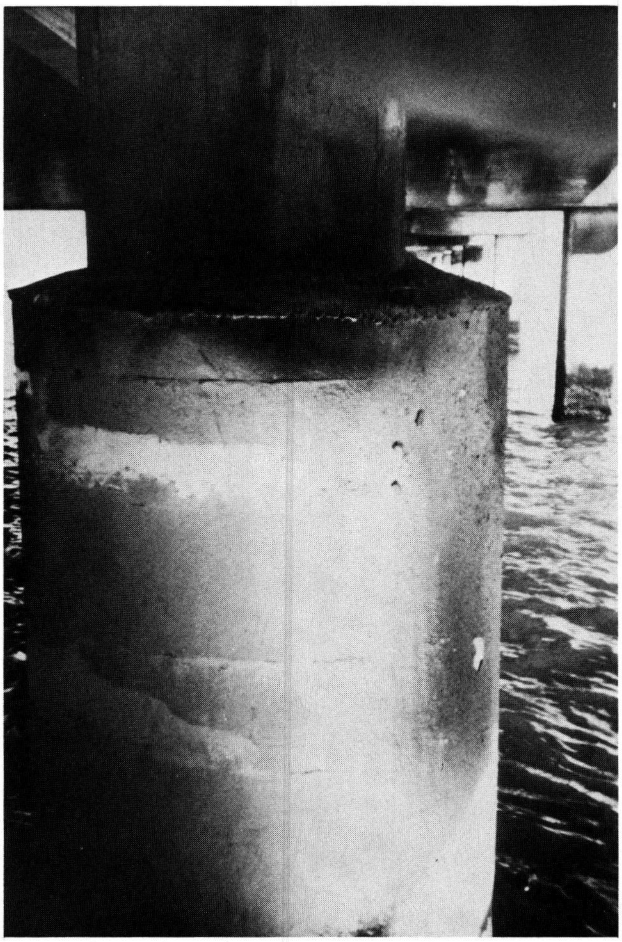


Figure 16. Round fiberglass jacket, concrete filled.

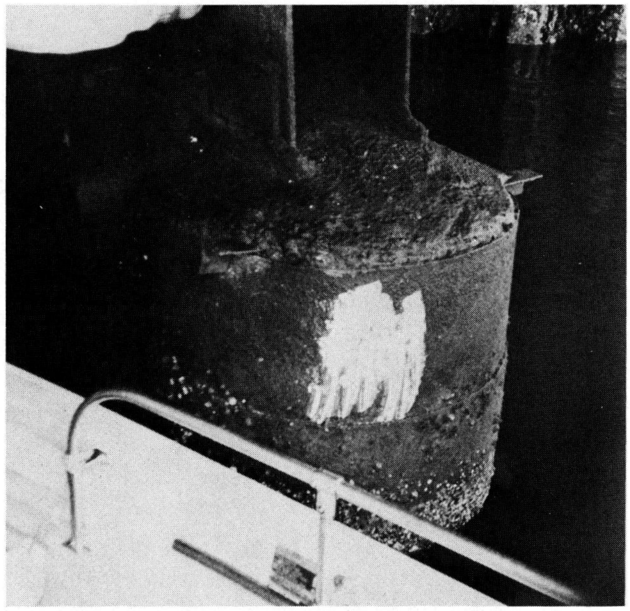


Figure 17. Round fiberglass jacket; surface has been scraped.

can then be removed or left in place to provide protection. Their high initial cost can be offset by reusing these durable forms. Removal of the forms also allows for monitoring of the performance of the repair. These jackets have been observed to have a tendency to become dislodged. Figures 18 and 19 show this repair technique in operation.

Sheet Piling

Sheet piling with backfill is a type of jacketing that is very effective in isolating the concrete from its environment. It can be filled with either concrete grout or earth with a concrete cap. The latter can also be designed to resist severe impact damage.

Crack Sealing

Epoxy Injection

Epoxy injection is a method by which low viscosity epoxy is pressure injected into a crack to restore full structural capacity and to stop corrosion. It has been used successfully under water and can seal cracks as narrow as 0.002 in. Its aesthetic value is questionable, however.

Other Resin Grouts

Other resin grouts for crack injection are currently being developed. These resins have the advantage of reacting with the water that is inside the crack and not simply displacing it. This results in there being no residual film of water left between the inside concrete surface and the injection material.

Sacrificial Concrete Collar

In this method, a nonstructural concrete collar is cast around structural

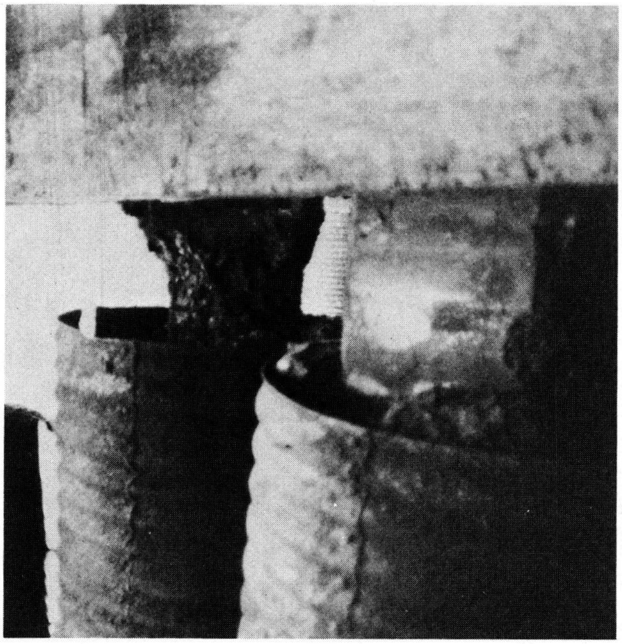


Figure 18. Corrugated metal jacket.

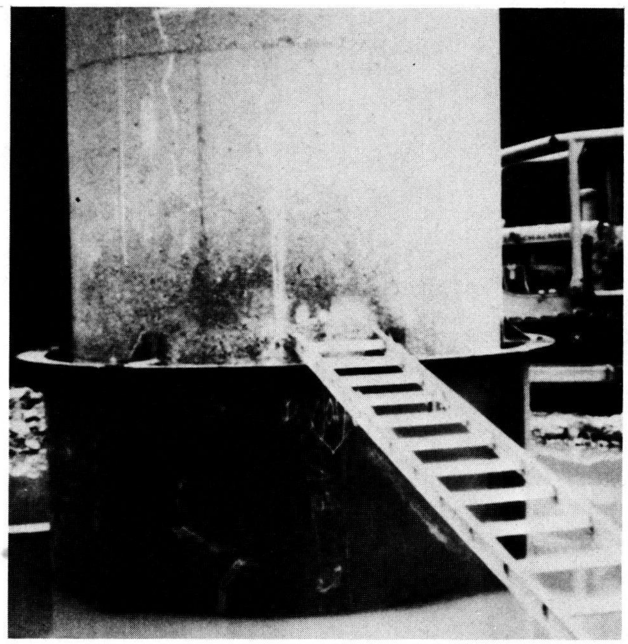


Figure 19. Steel collar jacket.

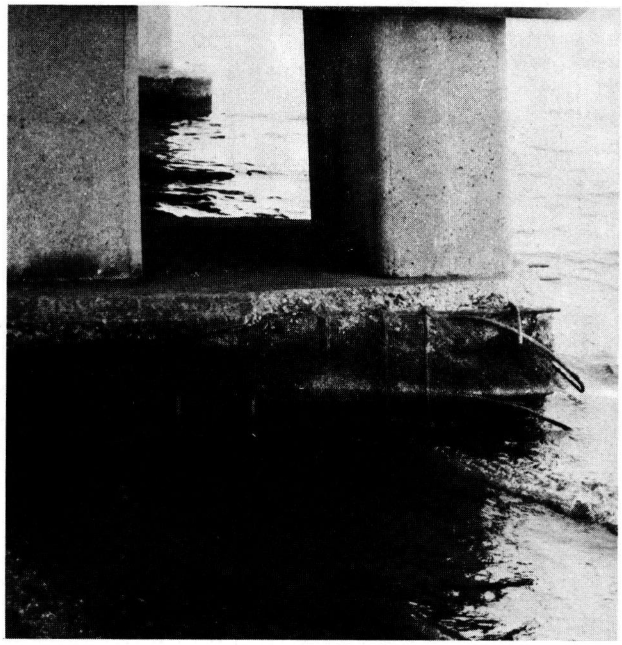


Figure 20. Sacrificial concrete armament.

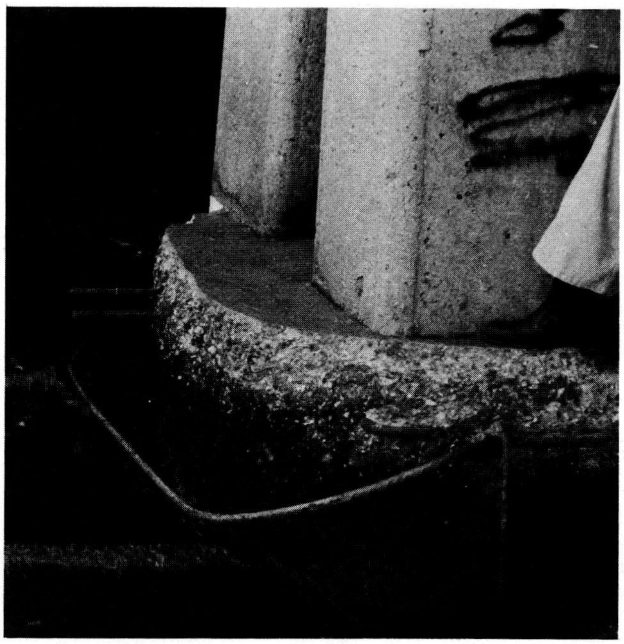


Figure 21. Sacrificial concrete armament.

concrete usually at the waterline only. When the sacrificial concrete deteriorates it is replaced. This method is expensive and increases the dead load to such a degree that the decision to use this procedure may depend on a structural analysis. Examples are shown in Figures 20 and 21.

Grout Repair

A variety of epoxies and concretes with modifiers or admixtures are available for the underwater resurfacing of large areas of deterioration and/or section loss. These may be used in conjunction with pile jackets or formwork and may or may not include sandblasting of the reinforcing steel. With the proper grout, they can be an effective repair measure. Some commonly used grouts are:

- Portland cement concrete with modifiers and mixtures. See Appendix C for further details.
- Latex-modified concrete slurry (17, p 532).
- High alumina cement (21, 22).
- Sulfur impregnated concrete (22).
- Epoxy mortar grout.
- Gun-applied mortar (16, p 532 23, pp 509-526). See Figures 22 and 23 for examples of typical failure.
- Preplaced aggregate concrete.

The question has been raised as to whether permanent formwork helps to protect a repaired area or whether it simply hides additional deterioration. It is known that water absorbent forms, such as wood, will dewater the concrete mix adjacent to it, making the surface harder. If these forms are left in place for an extended period of time until a repair is fully cured, they can then be removed so that assessment of the repair can be undertaken. Permanent forms, however, promote wick action.

When patching chloride contaminated concrete with a patch of fresh concrete, if the patch comes in contact with the reinforcing steel, a corrosion cell can be established. In this instance, there is an increased potential for corrosion that simply shifts to surrounding cathodic areas of the same bars forming an anodic area and corrosion then continues. This situation may be remedied by coating the inside of the concrete cavity and all exposed reinforcing steel with epoxy bonding compound to electrically insulate the fresh patch.

Passive Cathodic Protection

A sacrificial zinc anode, weighing 4 to 10 pounds, is attached directly to an exposed reinforcing steel bar during the underwater inspection. This method is quick, is simple, and arrests corrosion of bars that are completely exposed for up to 2 years (19).

Active Cathodic Protection

Active cathodic protection of partially submerged concrete bridge substructures is not currently practicable. Bridge decks offer a relatively uniform potential for corrosion, while substructures have more complex physics. When concrete is continuous through all three zones (subterranean, underwater, and atmospheric), the reinforcing steel is subject to three potentials for corrosion. Steel piles have successfully been cathodically protected because they have the advantage of being in direct contact with an electrolytic solution, seawater, whereas the reinforcing steel in concrete is initially insulated from it. As the cover deteriorates and the electrical conductivity of the cover increases, that portion becomes highly active, accelerating corrosion.

SUMMARY

Repair of Concrete v. Arresting of Deterioration

A few of the methods that have been discussed are best suited for only new construction. The others are considered either methods to repair concrete deterioration or methods to arrest concrete deterioration. The distinction is that methods to repair deterioration typically are simply those which put back something that may have been inferior in the first place and which do not address the cause of deterioration. On the other hand, methods to arrest deterioration are those which attempt to intervene in the natural chain of events known as deterioration and to slow or even to arrest its continuation.

Case Histories

Case histories of specific repairs are included in Appendix E. They are presented in work-sheet format so that the judgments provided by the owner and the researcher will not be construed as the final word on any particular repair method. Any assessment of a particular repair installation must be qualified with such factors as: conditions at the site on the day repairs were made, quality control, and field conditions since installation.

Table 1 summarizes the repair methods discussed in this chapter. It also indicates a qualitative "likelihood of success."

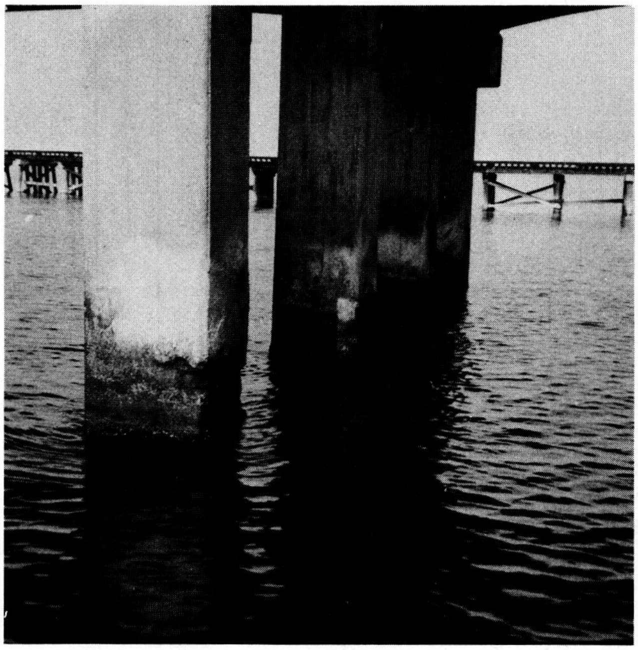


Figure 22. Gun-applied mortar (note deterioration).

Figure 23. Gun-applied mortar (note deterioration).

Table 1. Summary of repair methods (likelihood of success).

STAGE OF DETERIORATION	ABRASION	CORROSION	FREEZE-THAW	CHEMICAL ATTACK
INITIAL STAGE	1. Hydraulic Training (Fair)	1. Penetration Sealants (Poor)		1. Penetration Sealants (Poor)
BEGINNING OF THE PROPAGATION STAGE	1. Veneers (Good)	1. Surface Coatings (Poor)	1. Surface Coatings (Poor)	1. Veneers (Good) 2. Surface Coatings (Poor)
END OF THE PROPAGATION STAGE	1. Jackets (Good)	1. Jackets (Good) 2. Wraps (Fair)	1. Jackets (Fair)	1. Jackets (Good) 2. Wraps (Fair)
DESTRUCTION STAGE	1. Collar (Excellent) 2. Grout (Good)	1. Collar (Excellent) 2. Zinc Anode (Excellent) 3. Seal Crack (Good) 4. Grout (Fair)	1. Collar (Excellent) 2. Grout (Good)	1. Collar (Excellent) 2. Grout (Good)

Chapter Four

NEW OR IMPROVED METHODS TO ARREST CONCRETE DETERIORATION

"BRAINSTORMING" SESSION

Format for the Session

In order to generate new or improved methods to arrest concrete deterioration, a "brainstorming" session was conducted with representatives from industry and governmental agencies in attendance.

Essentially, arresting deterioration means, or at least implies, interfering with a progression of events that will occur naturally in a fairly well-defined order but at a varying rate, depending on the intensity of the various factors involved. On the basis of this premise, the approach to the brainstorming session was to outline to the participants the causes of concrete deterioration, as described below, in a step-by-step process. It was stated that deterioration begins with the initiation stage, progresses through the propagation stage, and concludes with the destruction stage. This premise was presented in three separate categories: salt water (hot), salt water (cold), and fresh water.

It was pointed out to the attendees that three points should be considered when developing a new or improved method to arrest concrete deterioration. First, the stage of deterioration of the member must be established within the progression of events that one wishes to arrest. Second, it must then be decided how best to arrest the deterioration at that point. Third, it should be determined whether or not it is economically feasible to do so. When the basic premises were established the "brainstorming" session was begun with the maximum amount of free participation encouraged.

Refinement of Parameters

It was decided that what would help the majority of maintenance engineers throughout the nation most was a quick, easy, and economical method to arrest concrete deterioration without the need for extensive evaluation. As an example, if 10 percent of the piles of a bridge were to begin to deteriorate, it could be assumed that the other piles were in the propagation stage of deterioration. It would be best then to look for an economical method that could be applied to all piles and not just the 10 percent that show deterioration.

Extensive evaluation could very well raise the cost of arresting deterioration in selected piers beyond that of arresting it in all piers by a sufficiently economical method. The technology necessary to identify a particular stage of deterioration is not within the scope of this project.

It was pointed out by the research team that repairs are typically undertaken during the destruction stage. This may be too late to effectively arrest deterioration. It was decided by all that the most benefit would be gained if methods could be devised to arrest deterioration in the initiation and in the propagation stages.

The consensus of the "braintorming" panel was that there is little difference between the rate of deterioration caused by hot or cold salt water. The representatives from the U.S. Navy mentioned several examples from their own experiences around the world confirming this. Therefore, it was decided to eliminate any distinction in deterioration rate resulting from differences in ambient temperatures.

It was also decided that the most cost-effective methods would be those that require a minimum of diver time and that are easy to apply. Cold water and cumbersome gear limit the abilities of the diver. Visibility is limited and in many cases nonexistent. This limits the application and the inspection of the preservation method employed. Currents and waves are dynamic forces that further reduce the efficiency of the diver. If everything else is ignored , the diver still has the problem of having no leverage. He floats in neutral buoyancy with no benefit of a surface to push against or of body weight to apply. Because of all these circumstances the diver is not the ideal contruction worker and everything he does is costly, time consuming, and relatively inefficient.

IDEAS RESULTING FROM THE "BRAINSTORMING" SESSION

Many ideas were presented and discussed at the "brainstorming" session. Following is a summary of those ideas without judgment as to their future value.

Tapes

Several forms of tapes were suggested that could be wrapped around a pile to protect it from its environment. This system was well received because it was envisioned to be convenient for a diver to apply. The tape would be supplied on a hand-held spool that the diver could easily grasp. Several materials were mentioned as being suitable for use as tapes.

• Mastic tape would provide a good chemical barrier and would aid in filling irregularities in the concrete surface. With elastic properties, it would fit a variety of shapes.

• Bituminous tape would provide an excellent chemical barrier. Its sticky texture would adhere to the concrete surface.

• Hardening tape that is pliable during its application and later sets up like a cast would offer abrasion resistance.

• Plastic tape would offer chemical resistance.

• A two-part system of tapes and/or coatings would combine the best of each component.

Sealants and Coatings

Several coatings were suggested as being beneficial in arresting concrete deterioration. It was realized that some of these materials cannot be applied under water. The attendees later discussed methods to dewater the application surface. Suggestions included:

• Cycloaliphatic polyurethane silicone elastometric membrane is a vapor permeable coating that expands into pores when it is wetted. However, it is not abrasion resistant and biological growth will rupture the membrane.

• Silica gel, which is now used on submerged glass as an antifouling agent, would discourage biological growth from rupturing sealing membranes.

• A coating with low cohesion and high adhesion will not become completely dislodged when biological growth is pulled from its surface.

• Liquid plastic coatings might be formulated to exhibit ideal qualities.

• Silicone latex emulsions are water repellant.

• Flaked glass in a mastic tape would stop oxygen ingress.

• Sacrificial coatings would stop chemical attack.

Other Methods

Various other methods were also discussed at the brainstorming session; these included the following:

• A dewatering cofferdam would permit the application of surface sealants to concrete which normally could not be applied under water. This would certainly increase the variety of sealants available. The device would be a small, clamp-on, light-weight unit.

• A floating inner tube device with a skirt beneath it would be helpful in arresting ice abrasion due to a fluctuating water level.

• Litmus-paper-type indicators that turn different colors would aid in the identification of the type of chemical attack that is occurring. This method would be quick and economical in comparison with a laboratory analysis of water samples.

• A chemical filter similar to an intrusion fence at a contruction site could be used to screen ions.

• A bubbler curtain similar to those used at marinas could be used to stop ice formation.

• A vulcanized rubber wrap could protect against chemical attack.

• An asphalt coating would seal the concrete surface.

• The concrete surface could be greased to make it hydrophobic.

• An electric charge could be applied to the concrete to drive out ions.

• The concrete could be encased in fresh water to provide a hospitable environment in contact with the concrete surface.

• A sacrificial pier could be built around the structural pier to isolate it from the aggressive environment.

"BRAINSTORMING" IDEAS THAT WARRANT FURTHER INVESTIGATION

Of the numerous ideas that were developed at the brainstorming session, two appeared to have significant potential to the research team. This conclusion was reached through an evaluation process made by each member of the research team and a weighting process resulting in a consensus opinion.

Those ideas are (1) the development of a multiple tape system and (2) the development of a procedure for applying coatings and sealants.

Multiple Tape System

It seems feasible that if materials could be found that would resist each of the four causes of deterioration, they could be formulated into separate or composite tapes that could be wrapped around a pile or column to isolate it from its environment. The system has been conceptualized as being applicable to piles and columns only. It would be of little use for walls and mass concrete.

It should be stressed that these tapes have not been developed. What is described here is the basis for a potential system.

These tapes would be on plastic spools about 1 ft. wide and would have buoyancy compensator bags built into them so that a diver could wrap them around a pile with ease while maintaining their neutral buoyancy. The tapes would be applied in a spiral pattern. Each layer would alternate between left-hand and right-hand spirals. Each wrapping sequence would begin at its lower limit of application and progress up the pile so that upper layers would overlap lower ones and the joints would tend to "shed water."

Abrasion Tape

Abrasion tape should be pliable during its installtion. Ideally, it should have a compressive strength at least as high as the abrasive material. Seven to 10 ksi would be a minimum compressive stress. It should have a moderate tensile strength to resist being dislodged. It should be smooth on its back side to minimize local turbulance, and the tape may be sticky on its face to aid in its application.

For economy, it can be formulated without chemical resistance for fresh water and with chemical resistance for salt water. It can also be resistant to the effects of freezing and thawing. This property of the tape may also be a specification to order option; however, its cost benefit should be investigated.

The tape could harden by hydration. Because tape by nature would be a relatively thin layer of material, plastic or fiber-reinforced hydraulic cement might be a good choice. This tape might be in the form of plastic packets filled with hydraulic cement on a plastic backing. The packets would slowly dissolve in the water trapped between layers of tape and release the hydraulic cement so that it may hydrate. Thorough mixing of the cement would be doubtful, however.

Other methods of hardening are also available. A two-component tape, as with epoxy, might be useful; however, thorough mixing of the components again is doubtful. Plastic cloth impregnated with epoxy would have good strength characteristics but would be more labor intensive. A high-strength cloth might also work.

Additionally, all tapes described herein should have a "quality-control-of-overlapping-joint" inspection line (QC overlap line) located 2 in. from each edge. This will allow a quick construction acceptance inspection after each layer of tape is applied.

Rubberized Asphalt Tape

Rubberized asphalt tape should be a thick pliable tape that is made of chemically inert material. Rubberized asphalt is specified here; however, other materials may prove beneficial. It should be sticky on its face to aid in its application and have a strong backing to increase the tensile strength of the tape. It should also have QC overlap lines.

Plastic Foam Tape

Laboratory tests indicated that the extent of damage to a concrete sample as a result of freezing and thawing is directly proportional to the rate of cooling. Through the use of plastic foam tape, an attempt is made to reduce the exodus of thermal energy from the concrete and allow water to migrate from the capillaries to internal voids or the surface before it freezes.

This tape should be thick and pliable with a high thermal resistivity factor. It should have a moderate amount of chemical resistance and may be sticky on its face to aid in its application and have a strong backing to increase the tensile strength of the tape. It should also have QC overlap lines.

Conductive Tape

Conductive tape is envisioned as a pliable tape that would impart cathodic protection. It would conduct electricity either by means of embedded wires, or more perfectly, by means of the electrical conductivity of the material itself. This may be accomplished with conductive mastic or woven graphite fiber. It is possible that the tape may only be required above the waterline and that a single wire would be required below the waterline. This is because the water provides the electrolyte to distribute the charge.

A problem that will have to be solved is the venting of gases that will be produced. Chlorine gas, which will be one by-product, is so active it will eat away epoxy. This may be overcome if the top seal is gas permeable.

The tape should be sticky on its face and have a strong backing to aid in its application. It should also have QC overlap lines.

Permutations

Each of these four tapes would be formulated to protect against the four forms of deterioration independently. In a naturally occurring environment, however, a combination of several forces is usually at work to deteriorate concrete. For this reason, a combination of the tapes described above would afford the best protection.

Figure 24 shows which tapes would be used for combined attack. The important element in this figure is the order of application. For example, Box 3 prescribes that abrasion tape be placed <u>over</u> rubberized asphalt tape for combined abrasion and chemical attack. This tape system would be ineffective if it were reversed.

	Abrasion	Corrosion	Freeze-Thaw	Chemical Attack
Abrasion	Abrasion Tape			
Corrosion	- BOX 1 - Abrasion Tape over Conductive Tape	Conductive Tape		
Freeze-Thaw	- BOX 2 - Abrasion Tape over Plastic Foam Tape	- BOX 4 - Plastic Foam Tape over Conductive Tape	Plastic Foam Tape	
Chemical Attack	- BOX 3 - Abrasion Tape over Rubberized Asphalt Tape	- BOX 5 - Rubberized Asphalt Tape over Conductive Tape	- BOX 6 - Rubberized Asphalt Tape over Plastic Foam Tape	Rubberized Asphalt Tape

Figure 24. Combined attack: propagation stage corrective action.

	Corrosion	Freeze-Thaw	Chemical Attack
Abrasion & Freeze Thaw	BOX 7 Abrasion Tape over Plastic Foam Tape over Conductive Tape		
Abrasion & Chemical Attack	BOX 8 Abrasion Tape with Chemical Resistance over Conductive Tape	BOX 9 Abrasion Tape with Chemical Resistance over Plastic Foam Tape	
Freeze-Thaw and Corrosion			BOX 10 Rubberized Asphalt Tape over Plastic Foam Tape over Conductive Tape
Abrasion, Freeze-Thaw and Corrosion			BOX 11 Abrasion Tape with Chemical Resistance over Rubberized Asphalt Tape over Plastic Foam Tape over Conductive Tape

Figure 25. Three and four combined attack.

Figure 25 takes this concept a step further by describing tape systems to combat the simultaneous onslaught of three or four different types of deterioration. It may be noted that Box 11 addresses all four of the causes of deterioration discussed in this report.

Limits of Application

To be effective the tapes do not need to extend completely from the mud line to 10 ft. above the level of extreme high tide. Economy of materials will be achieved if each tape is applied where it will do the most good. The order of tape application is also an important consideration so that optimum use is achieved. Starting from the outside and proceeding inward through each layer, the limit of application of each tape is described below and presented in Figure 26.

Abrasion tape is best placed on the outside to provide a hard shell protection for the underlying layers. It will be needed in two zones. At the mud line, it will need to extend from just above the mud line to some depth below the mud line to compensate for the scouring action that occurs at a pile during periods of high water velocity. At the waterline, the tape should extend just beyond the limits of extreme low tide to extreme high tide.

Rubberized asphalt tape would be required next if chemical attack is a problem. It would extend from the mud line to the top of the splash zone and would also protect any underlying layers. As mentioned in Chapter Three, wick action will draw in water and chemicals at the bottom of a repair and expell water vapors from the top, leaving a high concentration of chemicals at the concrete surface. To arrest this action, effective top and bottom seals will need to be designed.

Plastic foam tape would be needed next to protect the concrete from falling air temperatures. This would necessitate an application zone from just below the extreme low tide line to the top of the splash zone.

Conductive tape would be the innermost layer because it needs to be in direct contact with the concrete surface. It would be required from below the mud line to the top of the splash zone.

The economy of labor can be maximized by reducing the number of tapes used. Possibly, conductive tape and rubberized asphalt tape could be offered alternately as a composite. Limiting the number of tapes will also reduce the stress on the diver by reducing the number of descents that will be required. As a result, the total economy will be a trade-off between labor and materials, i.e., using four separate tapes or one combined tape.

Top and Bottom Seals

Top and bottom seals present two interesting problems that were discussed previously: wick action and the venting of gases. It would appear that both problems could be solved by developing a watertight bottom seal and a vapor-permeable top seal (see Fig. 27). The top seal would simply keep water out. With this arrangement, gases and water vapor can be vented. This would cause the pile to dry out, thus reducing electrical conductivity and chemical activity. Some problems remain, however. Even if the overlapping joint and the bottom seal were watertight, water would still percolate through the concrete capillaries producing wick action. In this case the vapor-permeable top seal would only aggravate the situation.

A method to seal the capillaries deep below the water surface would be beneficial. One possible solution might be placing chemicals at the bottom of the bottom seal so that they would be drawn up into the capillaries, react with the concrete, and reduce its permeability.

Typical Installation

Figure 28 depicts what is described in Box 11 of Figure 25. This system is intended to arrest all four causes of concrete deterioration. The dimensions shown are for illustrative purposes only.

Tape Applicators

In an effort to minimize diver effort, various tape applicators were considered. The simplest is shown in Figure 29 and consists of an axle through the spool and two "U" shaped handlebars set at 90 degrees to each other. A hand brake, much like that on a bicycle, is provided on one handlebar and would be capable of locking similar to a parking brake. This would allow the diver the ability to release the spool and not have it float away. As mentioned previously, the spool itself would have buoyancy compensation to compensate for changes in depth and the weight of the tape remaining on the spool. All materials would have to be corrosion resistant and chemically inert.

The diver operates the applicator by holding the handlebars and swimming spirally up the pile. Because a second diver is required on any diving operation, this worker follows behind pulling the tape taut and assures a uniform overlapping joint. The second diver then applies pressure with a device much like a rolling pin to squeeze out trapped water.

A second applicator, shown in Figure 30, has the rolling pin built into the frame. The diver grips the device near the roller and swims forward, guiding the tape and squeezing out trapped water at the same time. The second diver in this operation acts as a construction inspector, reducing

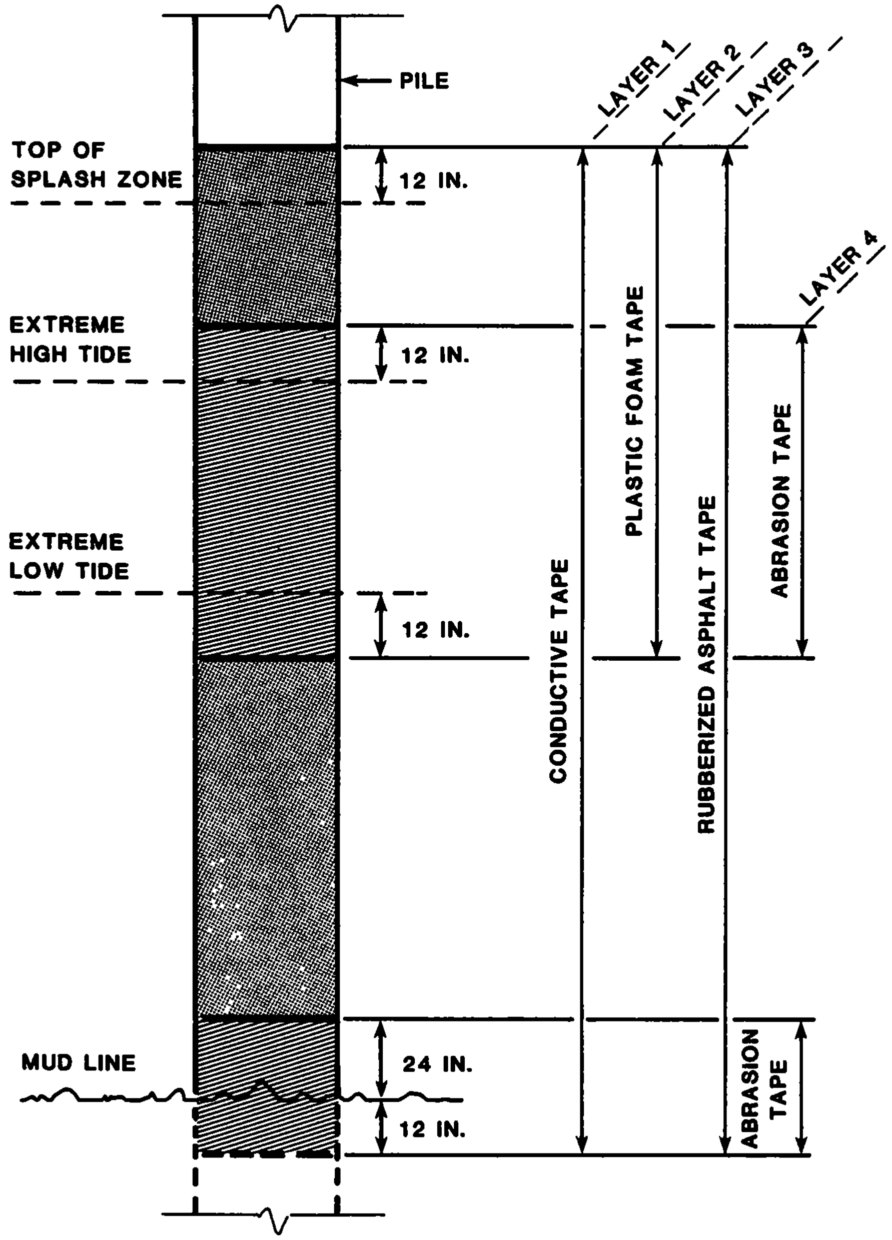


Figure 26. Limits of application.

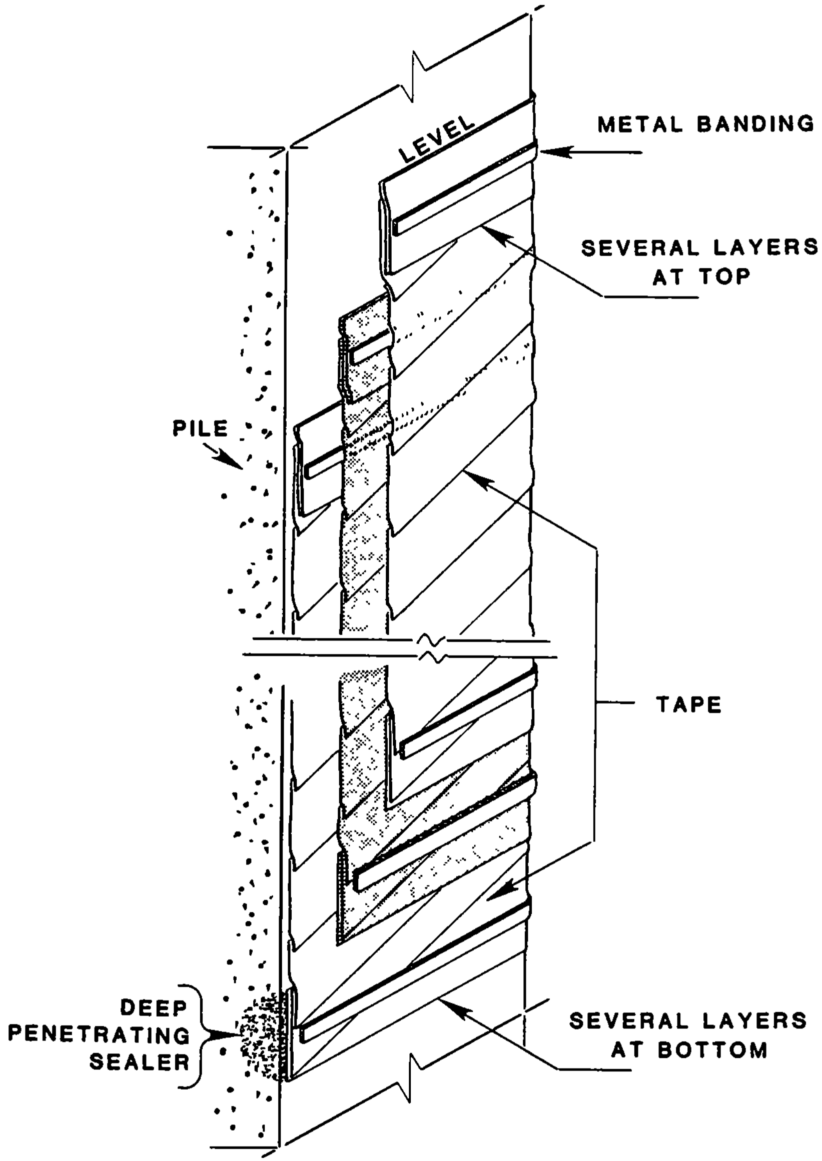


Figure 27. Top and bottom seal details.

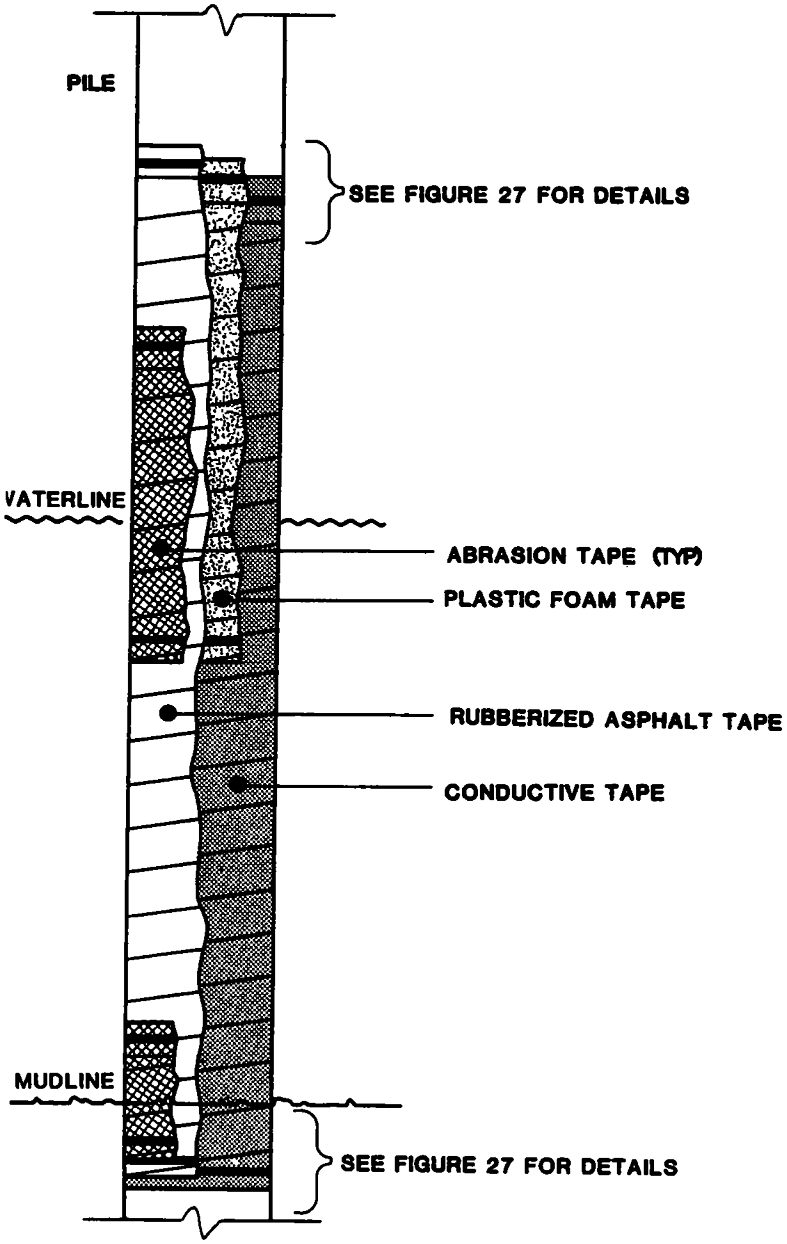


Figure 28. Multiple tape installation example.

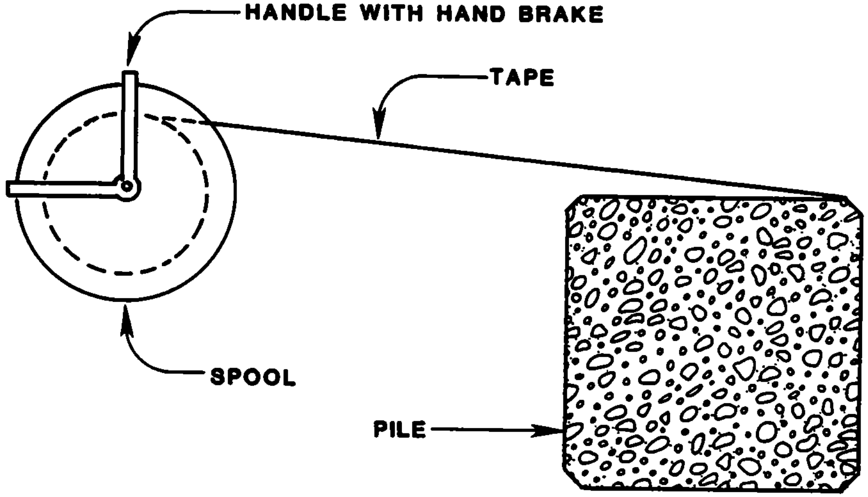


Figure 29. Tape applicator.

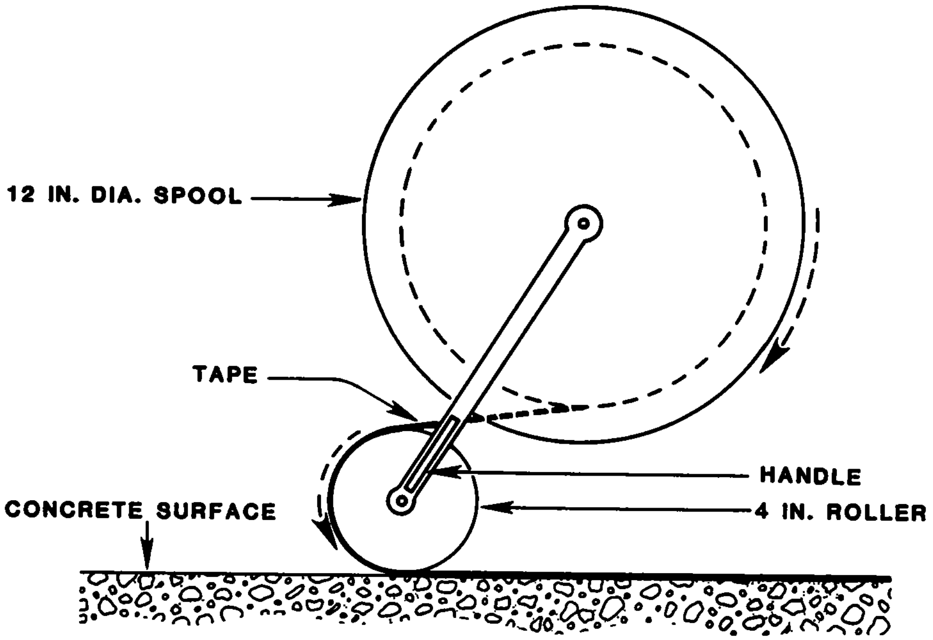


Figure 30. Tape applicator.

the complexity of the operation by a step for each tape that is applied.

Both the tapes and the tape applications are an attempt to envision something that would appear feasible. Field tests will be required in order to determine their true potential.

Dewatering Cofferdam

The dewatering cofferdam device was first described at the brainstorming session as a small clamp-on unit. It would facilitate several operations. First, a pile could be steam cleaned below the waterline. Acid etching might be possible with this device. The pile could then be allowed to dry for a couple of days. Hot air or infrared light could aid in the drying operation. The application of a wide variety of sealants and coatings would be possible because these materials can be applied in-the-dry. The form could even be flooded with a sealant to allow it time to soak into the concrete pores with slight hydraulic pressure.

This device could also be used as a reusable form for the pouring of concrete. Curing times for all these materials can be

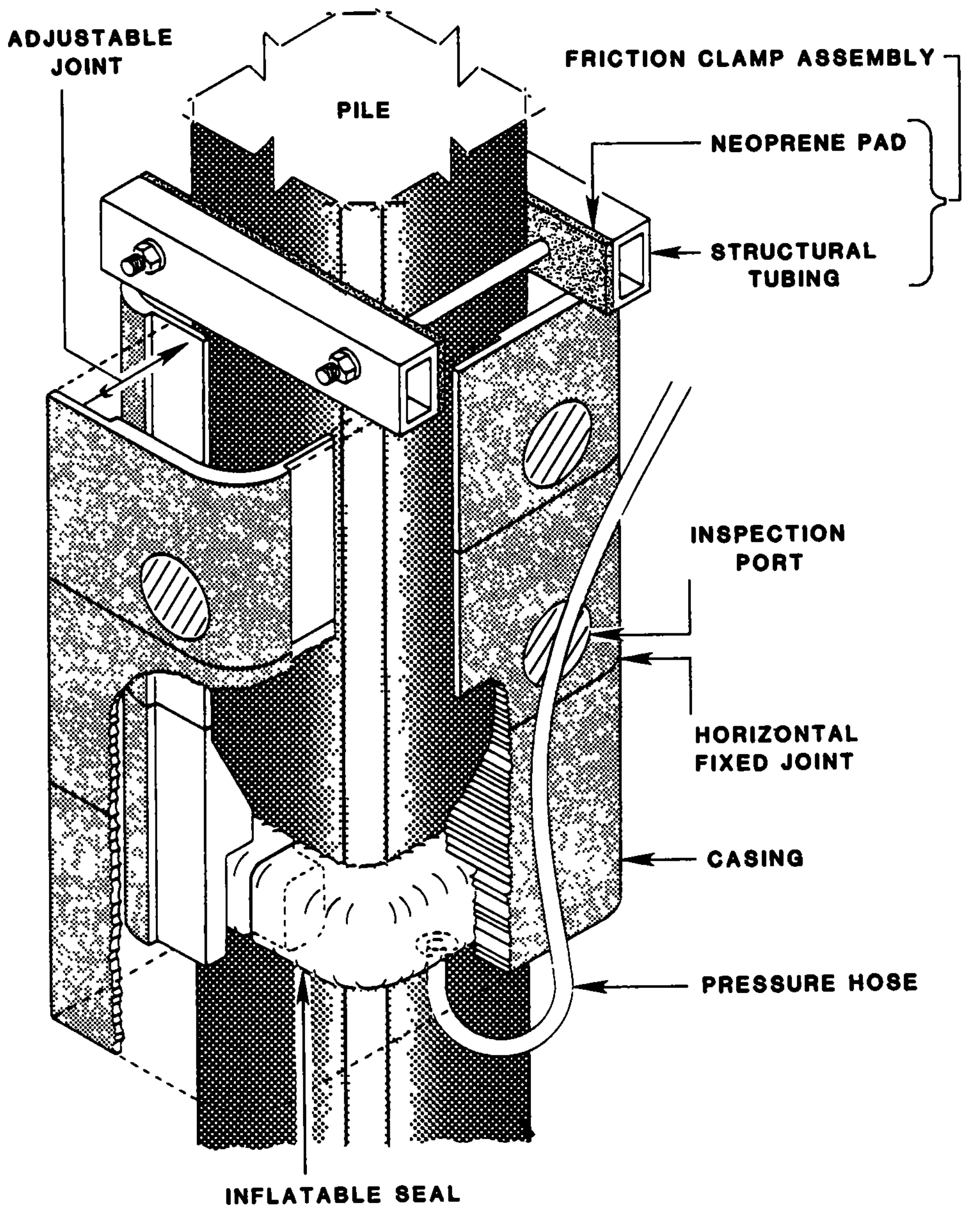


Figure 31. Dewatering cofferdam.

extended over several days. In subsequent discussions, it was decided that diver time could be minimized, if not eliminated, by requiring the device to be completely operational from the surface. This would mean that the bottom seal would have to be installed without the aid of a diver.

Figure 31 shows the dewatering cofferdam in place around a pile. To do this without a diver, the pile is first cleaned. This may be done by scraping below and sandblasting above the waterline. If the dewatering cofferdam is to be used as a reusable concrete form, a plastic form lining that is not shown in the figure is attached to the pile. This form liner will also provide additional curing after the form is removed. The casing and any banding is then assembled around the pile.

The inflatable bottom seal is placed around the pile and its two ends are connected. The seal is snapped onto the casing and retracted from the pile face. The casing is then lowered into position and temporarily secured. The friction clamp is assembled next, bolted in place, and the casing drawn up snug against the bottom of the clamp. The bottom seal is inflated. The seal may be either pneunatic or hydraulic in nature, depending on which is most advantageous. The water is then pumped out from within the casing.

To remove the dewatering cofferdam, the pressure release valve located above the surface is opened, allowing the inflatable seal to deflate. It is retracted from the pile face by means of straps. After the casing has flooded, the friction clamp is removed and the casing lifted out of the water and dismantled. If the cofferdam was used as a concrete form, quick-release latches (not shown) will need to be thrown to release the vertical joints so that the casing can be removed.

To minimize the cost of the device and maximize the versatility, the casing should be constructed in 4-ft. sections with horizontal fixed joints to accommodate tidal, wave, and splash zone variations. It also should have vertical adjusting joints. This would allow one casing to fit a range of pile sizes. The length of the inflatable seal will depend on the pile size. The bottom section can come in two models, one for square piles and one for round piles. The size of the round pile bottom section would also depend on the pile size.

The number of 4-ft. sections that will be needed will depend on condition at the site. The area to be covered with sealants would extend from 1 ft. below the level of extreme low tide to the top of the splash zone. Beyond this, a 1 ft. sump zone would allow for condensation. The remaining length can be used above the splash zone as a free board.

Design and details were also considered. Initial computations were run on the friction clamp to assure strength and torsional stability without the need for excessive member weight. Inspection ports were provided for quality assurance and all metal parts should be either galvanized steel or aluminum. It is realized that much development work remains in order to make this design a working model.

Sprayers

In an effort to minimize the buoyancy force exerted on the dewatering cofferdam, the inside clearance had to be only a few inches. Working in such a small space became the next concern. Methods of applying sealants and coating were discussed.

One possibility would be a fan sprayer, shown in Figure 32, on a hollow shaft at a right angle to it, which could be inserted inside the cofferdam. Other possibilities include a roller or a brush on a hollow shaft which would supply the sealant at the lower end.

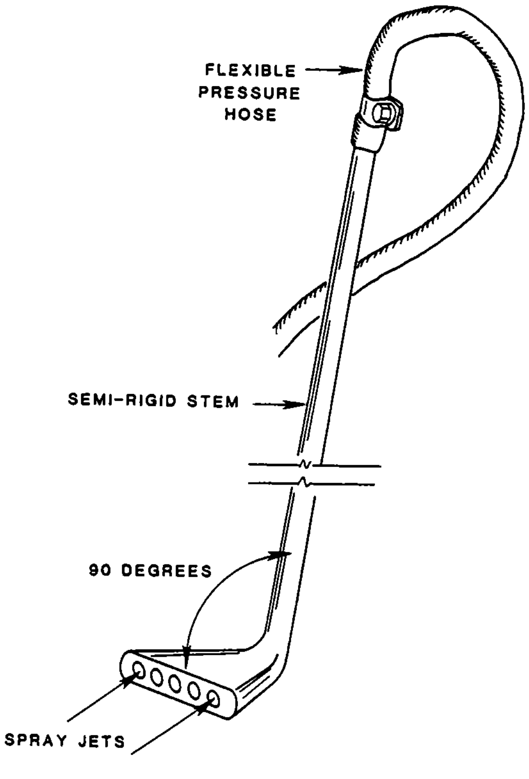


Figure 32. Fan sprayer.

Figure 33 depicts a sprayer apparatus which would be assembled around the pile before the dewatering cofferdam was pumped dry. This device is adjustable to accommodate a range of pile sizes. The device would be lowered to the bottom of the cofferdam, and then would begin spraying as the device is raised back to the top. The device would require a single lifting cable, and the pressure hose that supplies sealants from the surface would be attached to it so that the hose will be retracted as the device is raised. The stand-off wheels maintain the optimum spraying distance.

As an alternative to the above design, the device may simply consist of an adjustable frame of similar configuration with a flexible hose snapped to it. The hose would be disposable. This alternate is proposed to alleviate anticipated problems due to clogged spray jets and stuck slip joints. The alternate design would minimize down-time and eliminate the repetitive cleaning operation.

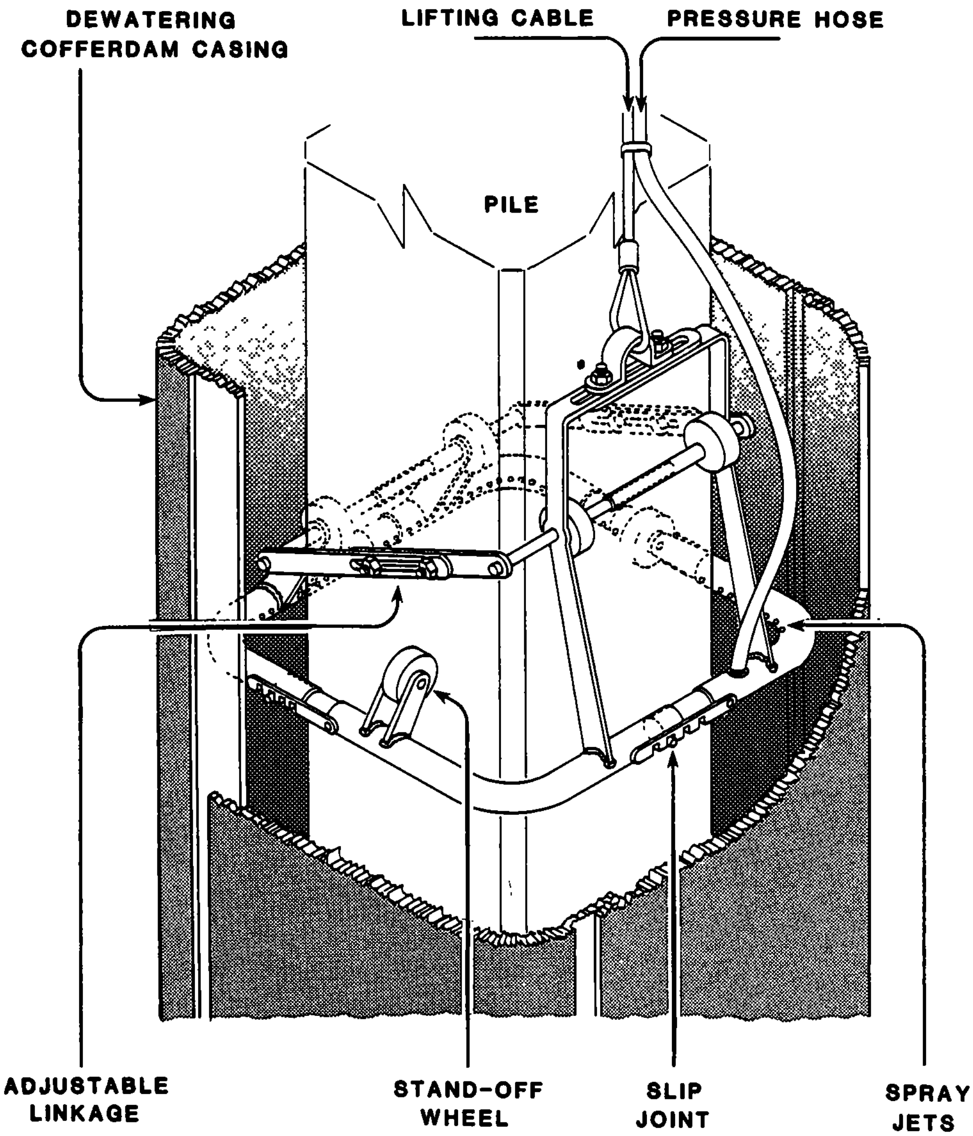


Figure 33. Sprayer apparatus inside dewatering cofferdam.

Chapter Five

CONCLUSIONS, RECOMMENDATIONS AND RESEARCH NEEDS

CONCLUSIONS

Inspection Techniques

Numerous techniques are presently available for the assessment of deficiencies in substructure units under water. With present technology, some are more suitable than others. Techniques that may someday have application for underwater use with further development include the following.

1. Assessing deficiencies with the aid of definitions based on the urgency of corrective action can be of help to maintenance engineers.

2. A rating modification system which accounts for variations in the rate of deterioration due to the history, environment, geography, and future land use near a bridge site can be applied to an initial assessment to more consistently depict the true immediacy of corrective action.

Substructure Analysis

1. State highway agencies usually analyze a bridge substructure only when a relatively obvious deficiency exists.

2. Most states feel that there is no need to analyze the effect that a deficiency has on capacity if repairs are promptly executed.

General Concrete Deterioration

1. There are three stages of deterioration: initiation, propagation, and destruction. Once it is determined which state of deterioration a structure is in, a repair process can be selected.

2. Repairs are usually undertaken only after extensive damage has occurred. This is due to financial limitations and the hidden nature of underwater deterioration.

3. Deterioration usually occurs first in the primary active zone defined as an area extending from the level of extreme low tide to the top of the splash zone. This accelerated rate of deterioration is due to the high availability of oxygen, the effects of freeze-thaw, and other factors.

Methods to Arrest Concrete Deterioration

1. Hydraulic training structures such as spurdikes, cofferdams, etc., address the primary causes of abrasion. The advantages of these structures are often limited because a structure which reduces scour and abrasion in one area may have a reverse effect elsewhere in the channel.

2. Penetrating sealants come in a wide variety; however, this research did not reveal any which appear to be applicable under water.

3. Surface coatings are available in a wide range of properties; however, they have enjoyed only limited success. Epoxies, in particular, tend to be highly complex systems that have had a history of requiring very stringent controls.

4. Jackets and wraps have produced varying degrees of success. Monitoring the performance of the system is necessary to determine if it is protecting the pile or simply hiding continued deterioration. Removable forms provide protection during curing and allow monitoring at a later date.

5. When sealing cracks by grouting or pressure injection, it is often questionable as to whether or not the repair has arrested deterioration. To insure that the repair is effective, a monitoring system is necessary. For repairs such as these, epoxy grout has shown the most promise.

New or Improved Methods to Arrest Concrete Deterioration

1. Methods that are quick and economical are needed to arrest concrete deterioration without the requirement for extensive evaluation.

2. Diver time and effort should be minimized for use in these methods.

RECOMMENDATIONS

Inspection

The development of several testing devices for underwater use would aid the maintenance engineer in evaluating the structural strength of bridge substructures.

Concrete

1. A polarization resistance device would be capable of the underwater measurement of the actual rate of corrosion of reinforcing steel.

2. A test block permanently attached to the substructure in a protected location would serve as a sample of the

original concrete poured at the time of construction. This block, which could be an outcropping on the pier cap, would aid the engineer in calibrating present and future test equipment.

3. Provisions should be made on existing piling as well as at the time of construction for an electrical connection to be made to the reinforcing steel in the substructure so that the voltage potential readings can be taken to monitor deterioration. This connection should be of trade standard quality and be situated in a protected location. Substructure units to be equipped should be distributed in shallow as well as deep water. Determination of which units will corrode first should not be of great concern because those which do not corrode will serve as a negative control.

4. Research into predicting a time frame of deterioration would be a help to the maintenance engineer in predicting when a structure will need repairs. For example, if the potential for corrosion of reinforcing steel could be observed and correlated to the "time to deterioration," an approximation could be made as to when corrosion will commence and when it will become a problem. This could be accomplished with something as simple as a graph with a "family of prediction curves" on which field data points can be plotted.

Steel

1. A steel strength testing device would be capable of determining the strength of existing piles under water. This would eliminate the need for coupons and strain gages.

Timber

1. A timber cat scanner would be much like that which is currently under development for concrete.

Assessment of Deficiencies

1. The proposed guideline booklet (App. G) should be implemented to assess underwater deficiencies.

Existing Methods to Prevent Concrete Deterioration

Materials

1. Because the corner bar of a square pile is exposed to basically two planes of attack and failure, it deteriorates much faster than do bars that are located on the side faces. The development of economical and efficient means to fabricate circular precast piles would eliminate this problem.

Practices

1. Soaking a pile in clean water before driving it in salt water will prevent the pile from soaking up salt water after it is driven.

New or Improved Methods to Arrest Concrete Deterioration

1. The proposed system of tapes and application should be developed to isolate a concrete pile from its environment.

2. Development of usable tape applicators will make the tape system an attractive alternative.

3. Development of a dewatering cofferdam device will allow many activities to be performed in-the-dry and allow others to be performed that could not previously be used at all.

4. Development of a sprayer for applying sealants and coatings will greatly increase the usefulness of the dewatering cofferdam.

RESEARCH NEEDS

1. The entire decision-making process of whether a substructure unit deficiency should be repaired, replaced, or action deferred should be examined in detail. Guidelines are needed to aid the engineer in establishing various criteria to be used in this process.

- Methods need to be examined to identify the stage of deterioration of a particular bridge substructure. The premise of an initiation, propagation, and destruction stage of deterioration can be applied to all building materials. The methods examined will probably be a combination of structural strength evaluation techniques identified in Chapter Two.

- An evaluation of viable repair technique options available for the particular stage of deterioration that is found needs to be discussed and tailored to be incorporated into the decision process. Thus, research is required to develop a method of selection between alternate repair procedures. This method should be based on an objective comparison of cost, benefit, probable success rate, and life expectancy.

- Once a repair approach has been identified, a decision must be made whether the preservation procedures are warranted at this time. A method of analysis of the cost benefit of performing repairs at a later stage of deterioration should be investigated. Economical savings may be realized if repairs are delayed until the optimum time frame for a specific preservation procedure. The alternative should also be investigated with regard to whether the estimated cost be spent on the repair or the money be applied towards funding a replacement structure.

2. Research that would parallel this study would detail prediction, assessment, and prevention of scour. Because of the sudden and often catastrophic nature of bridge failure due to scour, methods need to be examined that would predict and assess the risk of scour and a structure's susceptibility to scour. These methods, which might include computer modeling, would be based on the type of foundation material, type of substructure design, its susceptibility to scour, hydraulic characteristics of the stream, and statistics of failure. State-of-the-art methods to arrest scour should be investigated. New or improved methods to arrest scour should be developed.

3. In order to induce the private sector into developing new products, including those that were suggested in this report, the need for product development should be demonstrated by quantifying the underwater deterioration problem. A demand analysis of this information should reveal the potential market for particular products.

4. Because of the enthusiasm expressed by several states for the definitions of urgency of corrective action based on maintenance level and the modification chart, the proposed guideline booklet should be expanded to assess all elements of the deck, superstructure and substructure above as well as below the waterline. This research may eventually lead to the development of a comprehensive Bridge Maintenance Management System.

REFERENCES

1. American Public Works Association, History of Public Works in the United States. APWA (1976) p. 108.

2. Jones, R., "A Review of the Non-Destructive Testing of Concrete." Non-Destructive Testing of Concrete and Timber, Institution of Civil Engineers, London (1970) pp. 1-7.

3. Morgan, I.L., Ellinger, H.D., Klinksiek, R.V., and Thompson, J.N., "Examination of Concrete by Computerized Tomography." Journal, ACI, Vol. 77, No. 1 (January-February 1980) pp. 23.

4. Clear, K.C., "Cost Effective Rigid Concrete Construction and Rehabilitation in Adverse Environment." FHWA, FCP Annual Progress Report (Sept. 30, 1980) Unpublished, pp. 13-15.

5. Malhotra, J.M. and Carette, G., "Comparison of Pull-out Strength of Concrete with Compressive Strength of Cylinders and Cores, Pulse Velocity, and Rebound Number." Journal, ACI, Vol. 77, No. 3 (May-June 1980) p. 161.

6. Malhotra, J.M., Testing Hardened Concrete: Nondestructive Methods. Iowa State University Press, Ames and ACI, Detroit (1976) pp. 50-51.

7. Arni, H.T., "Impact and Penetration Tests of Portland Cement Concrete." HRR No. 378 (1972) p. 55.

8. Youshaw, R. and Dryer, C., "Underwater Non-destructive Testing of Ship Hull Welds." National Research Council, Unpublished, pp. 4-7.

9. Hopkins, F.F., Morgan, I.L., Ellinger, H.D., Klinksiek, R.V., Meyer, G.A., and Thompson, J.N., "Industrial Tomography Applications." Transactions on Nuclear Science, IEEE, Vol. NS-28, No. 2 (April 1981) p. 1718.

10. Eslyn, W.E. and Clark J.W., "Wood Bridges - Decay Inspection and Control." Agriculture Handbook No. 557 (October 1979) pp. 20-21.

11. McGee, D., The Timber Bridge Inspection Program in Washington State, FHWA (1975).

12. Orchard, D.F., Concrete Technology, Vol. 1, Applied Science Publishers, England (1979) pp. 438-441.

13. Dutruel, F. and Guyader, R., "Etude de la Corrosion des Canalisations en Beton." Monograph No. 7, Center d'Etudes et de Recherches de l'Industrie du Beton Manufacture, Epernon (Juin 1975) pp. 55-64.

14. Glassgold, I.L., "Repair of Seawater Structures - An Overview." Concrete International, Vol. 4, No. 3 (March 1982) pp. 50-52.

15. Perkins, P.H., Concrete Structures: Repair, Waterproofing and Protection. John Wiley and Sons, New York (1977) p. 190.

16. ACI Committee 201, "Guide to Durable Concrete." Journal, ACI, Vol. 74, No. 12 (December 1977) pp. 602-604.

17. Geymayr, G.W., "Repair of Concrete in Tropical Marine Environment." Performance of Concrete in Marine Environment, SP-65, ACI, Detroit (1980) pp. 535, 538.

18. "Protection of Concrete Structures." Consulting Engineering, London, Vol. 41, No. 2 (February 1977) pp. 35-37, 41.

19. Wakeman, C.M., Storer, J.W., and Liddell, O.E., "179 Years in Sea Water?" Materials Protection and Performance, Vol. 12, No. 1 (January 1973) p. 14.

20. Florida State Maintenance Office, Manual for Bridge Maintenance Planning and Repair Methods. Vol. I, Florida DOT, Unpublished, Item 844.

21. Heneghan, J.I., "Shotcrete Repair of Concrete Structures in Marine Environment." Performance of Concrete in Marine Environment, SP-65, ACI, Detroit (1980) pp. 517-518.

22. Houston, J.T., Atimtay, E. and Ferguson, P.M., "Corrosion of Reinforcing Steel Embedded in Structural Concrete." Report No. 112-1F, Center for Highway Research, University of Texas at Austin (March 1972) p. 15.

23. Neville, A.M., "Essentials of Strength and Durability of Various Types of Concrete with Special Reference to Sulfur." Journal, ACI, Vol. 76, No. 9 (September 1979) p. 984.

24. Greeves, I.S., "Underwater Concreting." Civil Engineering and Public Works Review, Vol. 68, No. 806 (1973) pp. 788-789.

25. Lane, R.O., "Abrasion Resistance." Significance of Tests and Properties of Concrete and Concrete Making Materials, STP-169B, ASTM Philadelphia (1978) pp. 349-352.

26. Cook, H.K., McCoy, W.J., "Influence of Chloride in Reinforced Concrete." Chloride Corrosion of Steel in Concrete, STP-629, ASTM, Philadelphia (1976) p. 23.

27. Mehta, P.K., "Effects of Cement Composition on Corrosion of Reinforcing Steel in Concrete." Chloride Corrosion of Steel in Concrete, STP-629, ASTM, Philadelphia (1976) p. 14.

28. ACI Committee 201, "Guide to Durable Concrete." ACI Journal, Vol. 74, No. 12 (1977) p. 583.

29. Biczok, Imre, Concrete Corrosion and Concrete Protection. Chemical Publishing Company, Inc., New York (1967) pp. 353-357.

30. Gjorv, Odd, "Durability of Concrete Structures in the Ocean Environment." Concrete Sea Structures, Proceedings of the Federation Internationale de la Precontrainte, London (1973) pp. 141-145.

31. Tyler, I.L., "Concrete in Marine Environment." Symposium on Concrete Construction in Aqueous Environments, ACI SP-8, ACI, Detroit (1964) pp. 2-6.

32. Jarocki, Walenty, "The Effects of Low Temperatures on the Hydraulic Structures of Concrete." Prace Technique Institute Bulletin No. 289, Warsaw (1966).

33. ACI Committee 212, "Guide for Use of Admixtures in Concrete." Proceedings, Journal ACI, Vol. 68, No. 9 (1971) p. 654.

34. Perkins, P.H., Concrete Structures: Repair, Waterproofing and Protection. John Wiley and Sons, New York (1977) p. 191.

35. Powers, T.C., "Freezing Effects on Concrete." Durability of Concrete, SP-47, ACI, Detroit (1975) pp. 1-12.

36. Woods, H., "Freezing and Thawing." Durability of Concrete Construction, ACI, Detroit (1968) pp. 15-20.

37. Litvin, G.G. and Sereda, P.V., "Particle Admixture for Enhanced Freeze-Thaw Resistance of Concrete." Cement and Concrete Research, Vol. 8, No. 1 (1978) p. 59.

Appendix A

BIBLIOGRAPHY

1. American Association of State Highway Officials, Manual of Maintenance Inspection of Bridges. AASHO, Washington, D.C. (1970) 71 pp.

2. American Association of State Highway and Transportation Officials, Manual of Maintenance Inspection of Bridges. AASHTO, Washington, D.C. (1978) 75 pp.

3. ACI Committee 201, "Guide to Durable Concrete." Journal, ACI, Vol. 74, No. 12 (December 1977) pp. 573-609.

4. ACI Committee 212, "Guide for Use of Admixtures in Concrete." ACI Journal Proceedings, Vol. 68, No. 9 (1971) pp. 646-676.

5. American Public Works Association, History of Public Works in the United States. A.P.W.A., Chicago (1976) 736 pp.

6. Anger, G., Ten-Division Influence Lines for Continuous Beams. Frederick Ungar Publishing Co., New York (1956) 247 pp.

7. Arni, H.T., "Impact and Penetration Tests of Portland Cement Concrete." HRR No. 378 (1972) pp. 55-67.

8. Biczok, Imre, Concrete Corrosion and Concrete Protection. Chemical Publishing Co., Inc., New York (1967) 543 pp.

9. Browne, R.D., "Mechanisms of Corrosion of Steel in Concrete in Relation to Design, Inspection, and Repair of Offshore and Coastal Structures." Performance of Concrete in Marine Environment, SP-65, ACI, Detroit (1980) pp. 169-204.

10. Cook, H.K., McCoy, W.J., "Influence of Chloride in Reinforced Concrete." Chloride Corrosion of Steel in Concrete, STP-629, ASTM, Philadelphia (1976) pp. 20-29.

11. Dutruel, F. and Guyader, R., "Etude de la Corrosion des Canalisations en Beton." Monograph No. 7, Center d'Etudes et de Recherches de l'Industrie du Benton Manufacture, Epernon (Juin 1975) 66 pp.

12. Eslyn, W.E. and Clark J.W., "Wood Bridges - Decay Inspection and Control." Agriculture Handbook No. 557 (October 1979) pp. 20-21.

13. Florida State Maintenance Office, Manual for Bridge Maintenance Planning and Repair Methods. Vol. I, Florida D.O.T., Unpublished. 144 pp.

14. Geymayr, G.W., "Repair of Concrete in Tropical Marine Environment." Performance of Concrete in Marine Environment, SP-65, ACI Detroit (1980) pp. 527-556.

15. Gjorv, Odd, "Durability of Concrete Structures in the Ocean Environment." Concrete Sea Structures, Proceedings of the Federation Internationale de la Precontrainte, London (1973) pp. 141-145.

16. Glassgold, I.L., "Repair of Seawater Structures - An Overview." Concrete International. Vol. 4, No. 3 (March 1982) pp. 48-53.

17. Greeves, I.S., "Underwater Concreting." Civil Engineering and Public Works Review, Vol. 68, No. 806 (1973) pp. 788-789.

18. Heneghan, J.I., "Shotcrete Repair of Concrete Structures in Marine Environment." Performance of Concrete in Marine Environment, SP-65 ACI, Detroit (1980) pp. 509-526.

19. Hopkins, F.F., Morgan, I.L., Ellinger, H.D., Klinksiek, R.V., Meyer, G.A. and Thompson, J.N., "Industrial Tomography Applications." Transactions on Nuclear Science, IEEE, Vol. NS-28, No. 2 (April 1981) pp. 1717-1720.

20. Houston, J. T., Atimtay, E. and Ferguson, P.M., "Corrosion of Reinforcing Steel Embedded in Structural Concrete." Report No. 112-1F, Center for Highway Research, University of Texas, Austin (March 1972) 131 pp.

21. Jarocki, Walenty, "The Effects of Low Temperatures on Hydraulic Structures of Concrete." Prace Technique Institute, Bulletin No. 289 Warsaw (1966).

22. Jones, R., "A Review of the Non-Destructive Testing of Concrete." Non-Destructive Testing of Concrete and Timber, Institution of Civil Engineers, London (1970) pp. 1-7.

23. Lane, R.O., "Abrasion Resistance." Significance of Tests and Properties of Concrete and Concrete Making Materials, STP-169B, ASTM Philadelphia (1978) pp. 349-352.

24. Litvin, G.G. and Sereda, P.J., "Particulate Admixture for Enhanced Freeze-Thaw Resistance of Concrete." Cement and Concrete Research, Vol. 8, No. 1 (1978) pp. 53-60.

25. Malhotra, J.M., Testing Hardened Concrete: Nondestructive Methods. Iowa State University Press, Ames also Monograph #9 ACI, Detroit (1976) 188 pp.

26. Malhotra, J.M. and Carette, G., "Comparison of Pull-out Strength of Concrete with Compressive Strength of Cylinders and Cores, Pulse Velocity, and Rebound Number." Journal, ACI, Vol. 77, No. 3 (May-June 1980) pp. 161-170.

27. McGee, D., The Timber Bridge Inspection Program in Washington State, FHWA (1975).

28. Mehta, P.K., "Effects of Cement Composition on Corrosion of Reinforcing Steel in Concrete". Chloride Corrosion of Steel in Concrete, STP-629, ASTM, Philadelphia (1976) pp. 20-29.

29. Morgan, I.L., Ellinger, H.D., Klinksiek, R.V. and Thompson, J.N., "Examination of Concrete by Computerized Tomography." Journal, ACI, Vol. 77, No. 1 (January-February 1980) pp. 23-27.

30. Neville, A.M., "Essentials of Strength and Durability of Various Types of Concrete with Special Reference to Sulfur." Journal, ACI, Vol. 76, No. 9 (Sept. 1979) pp. 973-996.

31. Orchard, D.F., Concrete Technology. Vol. 1, Applied Science Publishers (1979) 375 pp.

32. Performance of Concrete in Marine Environment. SP 65, ACI, Detroit (1980) 627 pp.

33. Perkins, P.H., Concrete Structures: Repair, Waterproofing and Protection. John Wiley and Sons, New York (1977) 302 pp.

34. Powers, T.C., "Freezing Effects on Concrete." Durability of Concrete. SP-47, ACI, Detroit (1975) pp. 1-12.

35. "Protection of Concrete Structures", Consulting Engineering, London, Vol. 41, No. 2 (February 1977) pp. 35-41.

36. Tyler, Ivan L., "Concrete in Marine Environment." Symposium on Concrete Construction in Aqueous Environments, ACI SP-8, ACI, Detroit (1964) pp. 2-6.

37. U.S. Dept. of Transportation, Federal Highway Administration, Bridge Inspector's Training Manual. US DOT, FHWA, Washington, D.C. (1970) 181 pp.

38. U.S. Dept. of Transportation, Federal Highway Administration, Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridges. US DOT, FHWA, Washington, D.C. (1977) 38 pp.

39. Wakeman, C.M., Storer, J.W. and Liddell, O.E., "179 Years in Sea Water?" Materials Protection and Performance, Vol. 12, No. 1 (January 1973) pp. 14-17.

40. Woods, Hubert, "Freezing and Thawing." Durability of Concrete Construction, ACI, Detroit (1968) pp. 15-20.

41. Youshaw, R. and Dryer C., "Underwater Non-destructive Testing of Ship Hull Welds." National Research Council, Unpublished, 31 pp.

Appendix B
RESEARCH APPROACH

ADDRESSES AND SAMPLE LETTERS

TO SOLICIT INFORMATION

HIGHWAY AGENCIES
U.S.A.

* Alabama State Highway Department
* Alaska Department of Highways
* California Department of Transportation
* Colorado Department of Highways
* Connecticut Bureau of Highways
* Florida Department of Transportation
* Georgia Department of Transportation
* Hawaii Department of Transportation
* Idaho Department of Highways
* Illinois Department of Transportation
* Kansas State Highway Commission
* Kentucky Department of Transportation
* Louisiana Department of Highways
* Maine Department of Transportation
* Maryland Department of Transportation
* Massachusetts Department of Public Works
* Michigan Department of State Highways and Transportation
* Mississippi State Highway Department
* Montana Department of Highways
* Nevada Department of Highways
* New Hampshire Department of Public Works and Highways
* New Jersey State Department of Transportation
* North Carolina Department of Transportation
* Oklahoma Department of Highways
* Oregon Highway Division
* Pennsylvania Department of Transportation
* Rhode Island Department of Transportation
* South Dakota Department of Transportation
* Tennessee Department of Transportation
* Texas Highway Department
* Vermont Agency of Transportation
* Virginia Department of Highways and Transportation
* West Virginia Department of Transportation
* Wyoming Highway Department

Puerto Rico Highway Authority

* Addressees that responded

OTHER AGENCIES

Highway Authorities

*N.Y. State Thruway Authority
*Massachusetts Turnpike Authority
*Mackinac Bridge Authority

Railroads

Seaboard Coastline Railroad
*Chicago and Northwest Transit Company
Southern Pacific Transit Company
*Kansas City Southern Railways
Chessie System
AT & Santa Fe Railway
Canadian National Railway
Federal Railroad Administration
*New Zealand Railways

Ports

*Port of Los Angeles
*Port Authority of NY and NJ

U.S. Government

*FHWA, Bridge Division, Hydraulic Branch
*U.S. Army, Corps of Engineers, Waterway Experimentation Station, Mississippi
U.S. Army, Coastal Engineering Research Center, Ft. Belvoir, VA
*U.S. Navy, Facilities Engineering Command
*U.S. Navy, Civil Engineering Laboratory, Port Hueneme
*U.S. Coast Guard
*U.S. Geological Survey, Water Resources Division, Denver
*Engineering and Research Center, Department of Interior
*U.S. Geological Survey, National Water Data Exchange
*National Bureau of Standards
U.S. Dept. of Commerce, National Technical Information Service
*U.S. Navy, Naval Surface Weapons Center, VA

Foreign Governments

Ministry of Works and Development, NZ
*National Roads Board, NZ
*Ministry of Transportation & Communications, Ontario, Canada
*National Road Administration, Sweden

COUNCILS, INSTITUTES, ASSOCIATIONS AND CENTERS

U.S.A.

*St. Anthony Falls Hydraulic Laboratory, University of Minnesota
Iowa Institute of Hydraulic Research
Center for Transportation Research, University of Texas
*National Association of Corrosion Engineers, Texas
ASCE, New York
*ACI, Detroit
*VDH&T Research Council, Virginia
*Transportation Laboratory, California Department of Transportation
*Planning and Research Division, Texas State Department of Highways and Public Transportation
*Fitz Engineering Laboratoy, LeHigh University
*Highway Research Information Service, Washington, D.C.
*Texas Transportation Institute, Texas A&M University
*Institute of Transportation and Traffic Engineering, University of California at Berkley
*National Ready Mixed Concrete Association, MD
*National Concrete Masonry Association, Virginia
*Balcones Research Center, University of Texas
*AREA, Washington, D.C.
ASTM, PA
Brookhaven National Laboratories, New York
*American Concrete Pile Association, Virginia
*Associated Reinforcing Bar Producers, Illinois
International Bridge, Tunnel and Turnpike Association, Washington, D.C.
*American Concrete Pipe Association

United Kingdom

*Transport and Road Research Laboratory
British Concrete Pumping Association
Corrosion Advice Bureau
*Cement and Concrete Association
*Reinforcement Manufacturers Association
*British Precast Concrete Federation
*Construction Industry Research and Information Association

West Germany

Verein Deutscher Zementwerke (Technical Association of the Cement Industry)
*Deutscher Beton-Verein (Concrete)
*Forschungsinstitut Der Zementindustrie (Research Institute of the Cement Industry)
Bundesverband Der Deutschen Zementindustrie (Cement Industry and Technical Advisory Services)

New Zealand

*Department of Construction, Experimental Building Section
*Portland Cement Association
Building Research Association
*Department of Scientific and Industrial Research
*Concrete Research Association
*Institution of Engineers

South Africa

National Building Research Institute
National Institute for Transport and Road Research
*Portland Cement Institute

Australia

Concrete Institute of Australia
*Cement and Concrete Association

Canada

*Portland Cement Association
*National Research Council
Engineering Institute of Canada

Belgium

Union Des Agglomeres De Ciment De Belgique (Belgian Cement Congolmerates Union)

Greece

Groupement Hellenique Du Beton
(Greek Association of Concrete)

Norway

Norsk Betongforening
(Norwegian Concrete Association)

Netherlands

Betonvereniging - Sekretariaat
(Netherlands Concrete Society)
Vereniging Van Bentonmortalfabrikanten in Nederland
(Dutch Ready-Mixed Concrete Association)

Sweden

Svenska Betonforeningen
(Swedish Concrete Association)

Finland

Suomen Betoniteollisuuden Keskusjarjesto Ry
(Association of the Concrete Industry in Finland)

Italy

Associazione Nazionale Fra i Produttori Di Manufatti in Cemento
(National Association of Producers and Manufacturers of Cement)

Japan

Public Works Research Institute, Japan

Switzerland

Verband Schweizerischer Transportbetonwerke
(Swiss Ready-Mixed Assoc.)

Denmark

Landsforeningen Dansk Betonvare-Industri
(Society Danish Concrete Industry)
Nordisk Vejteknisk Forbunds
(Danish Roads Federation)

Spain

Agrúpacion Nacional De Los Derivados Del Cemento
(National Association of Cement Producers)

France

*Federation Francaise De L'Industrie Du Beton
(French Federation of the Concrete Industry)
Centre d'Etudes et de Recherches de l'Industrie du Beton Manufacture

Thailand

*International Ferrocement Information Center

COMPANIES

U.S.A.

*Adhesive Engineering Company, California (Epoxy)
*American Chemical Corporation, California (Epoxy)
*American Colloid Co., Illinois (Waterproofing)
Cathodic Protection Services, TX
Chapman Chemical Company (Sonic Tester)
Exxon Corp.
*Fox Industries, Inc. (Pile Jackets)
*Froehling & Robertson, Inc., VA
*General Electric, N.Y. (Silicone Admixture)
*Gulf Oil Co.
*Gulf States Paper Corp., Alabama (Slope Stabilization)
*Harco Corporation, Ohio (Cathodic Protection)
Heath International, Inc., Michigan (Sonic Tester)
*Lee Turzillo Contracting Co.
*Maccaferri Gabion, Inc., MD
*Mobile Oil Corp.
Northeast Electronics, NH (Shigometer)
*Osmose Co., GA (Pile Jackets)
Peabody Testing, IL
*Poly-Carb, Inc., Ohio (Epoxy)
Raymond Concrete Pile Company
*Raymond International Buildiners, Inc., NJ (Erosion Control)
*Scientific Measurement Systems, Inc. (Cat Scan)
Shell Chemical Co.
*SIKA Chemical Corp., NY (Epoxy)
*Smithsonian Science Information Exchange, Inc.
*Structural Bonding Company, Michigan (Epoxy)
*Subsea International, LA
*Symons Corporation (Pile Jackets)
TAMMS Industries Co., IL
*The Hinchman Co. (Cathodic Protection)
*TYE Engineering Company (Hydraulic Research)
*ICE Products Research & Development Company (Pile Jacket)
Hitchins Vandex

New Zeland

Remedial Engineering
Morris & Wilson
Tedec., Ltd.
Stresscrete Industries

United Kingdom

Wells, Ltd.
*Taylor Woodrow Contracting, Ltd.

Canada

BC Research (Sonic Testing)

UNIVERSITIES

U.S.A.

West Virginia University
*Arizona University
University of Michigan
Massachusetts Institute of Technology
University of Virginia
University of Maryland
*Lehigh University
Cornell University
Virginia Polytechnic Institute
*Pennsyvania State University
University of California
Texas A & M University
*University of Minnesota
*University of Texas
*University of Illinois
South Dakota State University
Connecticut University

Thailand

*Asian Institute of Technology

Norway

*University of Trondheim

New Zealand

University of Auckland
University of Canterbury

South Africa

*University of Stellenbosch
*Rand Afrikaans University
*University of Natal
University of Cape Town
*University of Pretoria

EXPERTS

*FFM Chang (Hydraulics)
*Emmett M. Laursen (Scour)
*Bryan Mather, Corps of Engineers (Concrete)
Gordon Beecroft (Oregon Pile Study)
Ernst Renstrup, Denmark
*Dr. Roger D. Browne (Taylor-Woodrow Research Laboratory)
*Dr. Odd E. Gjorv

LIBRARIES

Department of Transportation Library, Washington, D.C.
Renesselaer Polytechnic Institute, Library, Troy, NY
Byrd, Tallamy, MacDonald and Lewis Library
Trans. Research Board Library, Washington, D.C.
Library of Congress, Washington, D.C.
Fairfax County Central Library

STATES VISITED AND

AGENCY PERSONNEL INTERVIEWED

MARYLAND

E. Williams Ensor

OREGON

John Wood
Gerald Test
Donald Dean

IDAHO

James Welch

MASSACHUSETTS

John Wood
Jim Gould
Joseph Donahue
Arthur Blunt
Jack Shutt
John Ahern

LOUSIANA

M. Pani
Douglas Hood
Sheldon Law
Larry Lucas
Ed Bodker

FLORIDA

Robert P. Brown
Jack Roberts
Julian McCrory
Bill Alford
Larry Davis

ATTENDEES -"BRAINSTORMING" SESSION

1. Mr. Craig A. Ballinger
   Office of Research
   Federal Highway Administration

2. Mr. Douglas H. Beeson
   Project Manager
   Byrd, Tallamy, MacDonald and Lewis

3. Mr. Roland H. Berger
   Advisory Committee Member
   Byrd, Tallamy, MacDonald and Lewis

4. Mr. Wade F. Casey
   Chesapeake Division
   Naval Facilities Engineering Command

5. Mr. Thomas L. Copas
Special Projects Engineer
Transportation Research Board

6. Mr. Donald R. Graber
Assistant Principal Investigator
Byrd, Tallamy, MacDonald and Lewis

7. Mr. James W. Harland
Acting Advisory Committee Member
Byrd, Tallamy, MacDonald and Lewis

8. Dr. Alfred Marzocchi
Exploratory Research Technical Center
Owens-Corning Fiberglas

9. Mr. Ronald L. Purvis
Advisory Committee Member
Byrd, Tallamy, MacDonald and Lewis

10. Dr. Anil K. Rastogi
Owens-Corning Fiberglas

11. Dr. Robert J. Reilly
Projects Engineer
Transportation Research Board

12. Mr. Martin C. Rissel
Principal Investigator
Byrd, Tallamy, MacDonald and Lewis

13. Mr. Philip T. Scola
Chesapeake Division
Naval Facilities Engineering Command

14. Mr. Schuyler B. Smith
Dow Corning Corporation

TELEPHONE INTERVIEW

Personnel Contacted

T.L. Cain	Maintenance Engineer	Alabama
Kenneth McGuire	Engineer	California
Milton Johnson	Engineer of Bridge Design	Connecticut
Jack Roberts	Engineer of Maintenance	Florida
Bob Brown	Corrosion Engineer	Florida
Larry Davis	Bridge Maintenance Planning Engineer	Florida
Steve L. Pittman	Assistant District Engineer, Maintenance	Georgia
James Welch	Bridge Maintenance Engineer	Idaho
Gayle Lane	Bridge Maintenance Engineer	Illinois
Charles Reichenbach	Bridge Maintenance Engineer, Chief	Kentucky
Al Dunn	Structures Maintenance Engineer	Louisiana
Everett Barnard	Assistant Bridge Maintenance Engineer	Maine
E. William Ensor	Chief, Bridge Inspector	Maryland
John N. Grim	Assistant Chief Engineer	Massachusetts
Richard McGinn	Structure Maintenance Engineer	Massachusetts
N.S. Walker	Engineer Bridge Maintenance	Michigan
James R. Newkirk	Engineer III	Mississippi
Alfred Westall	Assistant Chief Bridge Engineer	Nevada
Ed Swierz	State Bridge Engineer	New Hampshire
Rodger Blaisdell	Bridge Safety Inspector	New Hampshire
Warren Sunderland	State Bridge Engineer	New Jersey
Jimmy Lee	Head of Bridge Maintenance	North Carolina
John Wood	Bridge Maintenance Engineer	Oregon
A. Parola	District Bridge Engineer	Pennsylvania
John Ekiert	Acting District Bridge Engineer	Pennsylvania
Anthony Callia	Chief of Bridge Inspection	Rhode Island
Harry Anderson	Engineer	Rhode Island
Clyde Jundt	Bridge Maintenance Engineer	South Dakota
Ralph Banks	Supervising Field Engineer	Texas
Warren Tripp	Chief of Bridge Inspection and Design	Vermont
D.C. Harrier	Assistant Bridge Engineer	Virginia

Other Agencies

Orlando Doyle, Chief Engineer, MacKinac Bridge Authority
E. Van Beilen, Head Task Force Special Studies, Ministry of Transportation of Ontario, Canada
David Brookings, Bridge Engineer, Kansas City Southern Railway Company
Phil Scola, Engineer, Specialized Inspection, Underwater Investigation, Naval Engineering Facilities Command
Larry Anderson, Harbor Engineer I, Port of Los Angeles

TELEPHONE SURVEY NCHRP 10-16

NAME SURVEY RESPONSES

AGENCY 26 Responding Agencies

DATE

1 As part of the bridge inspection or other process, do you analyze existing substructure units?

18 States analyze when deficiency exists
1 States simply fix deficiencies
4 States (Fl & NC) always analyze (Vermont, Alabama)
5 States (SD & ME) never analyze (Nevada, Kansas City Southern Railway)

2 It would appear that in your [state / area / jurisdiction] there would be the possibility of particular difficulties with substructure units such as

Scour 20 states
Salt Water 11 states
Tides: 7 states
Fast Running Streams 6 states
Freeze - Thaw 7 Agencies
Industrial Waste 7 states
- ID Mining in basic soil
- FL Tannic acid and phosphate plant
- LA Paper mill
- NH Unknown
- PA Sewage outfall
- Ontario Paper pulp and steel plants
- GA Insecticide plant

Other	Difficulties
Nevada	Debris and Fluorides
Oregon	Borers
Virginia.	Ice
Port of Los Angeles	Borers

3 Has deterioration of concrete in the splash zone or below been a particular problem in fresh water? in salt water?

Salt water 12 States
Fresh water 6 States
- Debris impact Massachusetts
- Freeze-Thaw Massachusetts, Ontario, Kansas City Southern Railway
- Paper Mill Louisiana
- Mining in basic soil Idaho
- Tannic Acid Florida

4 Have you used or have you developed any methods which you consider unusual or unique to measure the adequacy of existing concrete underwater?

26 States No

5 In addition to engineering judgement, do you use or have you used any methods to measure and introduce the following deficiencies into a mathematical analysis in connection with the substructure inspection?

a Reduced compressive strength in timber due to progressive decay

Core 8 States
Resistance to drill 2 State
Sonic Test 1 State Researching
Judgement 1 State
Sounding 1 State
Pointed Probe 1 State

b Reduced compressive strength in concrete due to salt water attack

Core 8 States (California, Florida, Idaho, Louisiana, Maryland, Texas, Nevada)
Sound with Hammer 2 Agencies (Illinois, Kansas City Southern Railway)

c Corrosion of reinforcing steel

Measure reduced section 3 States

d Settlement of piers in simple spans, in continuous spans

No response

e Scour of spread footings

Evaluate sability 1 State

f Reduced friction capacity of piles due to scour

Calculate 1 State

g Reduced capacity of piles due to reduction in lateral support caused by scour

No response

6 Do you analyze for other types of deficiencies and, if so, how are they introduced into the computations?

24 States No

7 If your office has examples of unusual or novel approaches to any of the methods just discussed, would you be willing to forward them to us?

24 States No

8 Are there other divisions or sections within your agency that might have used or developed information in the area of substructure deficiencies (Design or Research Division, for example)?

Various answers Hydraulic Division, Materials Div Design Div , Bridge Rating Section, Mackinac Bridge Authority, Structural Engineer, Testing Division

9 Has you office developed guidelines and/or a rating system for the Structure Inventory and Appraisal (SI&A) sheet items 60 and 67 different from the one provided by FHWA to identify the urgency of corrective action? If os, would you please forward a copy?

Use FHWA 21 Agencies
Developed guidlines 6 States

10 What methods does you agency use to prevent, correct, or arrest concrete deterioration as a result of

a Corrosion of reinforcing steel

Jacket 8 States
Repour 7 States
Epoxy injection 1 State
Granite facing 1 State

b. Freeze-Thaw (In tidal zone, for example)

Jacket 5 States
Repour 5 States
Wrap 1 State
Granite facing 1 State
Prepacked concrete behind steel sheeting
Gun applied concrete 1 Agency

c Chemical attack

3 States Epoxy coat
2 States Jackets
1 State Granite facing
1 State Prepacked behind steel sheeting
3 States Recast

d Abrasion

4 States Jackets, 3 States Recast
1 State Granite facing, fenders, steel plates, timber forms left in place, iron nose, encase and fill, wrought iron jacket, C M collar, epoxy, high strength concrete

11 As part of this project, it will be necessary for us to visit some agencies to review their procedures and techniques in regard to these matters and also to visit some field sites that are appropriate

Would you be willing to spend some time with {me / our Principal Investigator}

or arrange for someone else from your agency to do so? If so, how much notice would you like and is there some time during the next few months when it would be inconvenient for some reason?

25 States Yes

Appendix C
HIGH QUALITY CONCRETE

SUGGESTED PROCEDURES FOR OBTAINING HIGH QUALITY CONCRETE AND GOOD CONSTRUCTION PRACTICES

The durability of concrete under water and in the splash zone depends on the mix design and the environment in which it will serve. Concrete which is designed to be of high quality for one environment may deteriorate rapidly in another. An example of this would be the use of air-entraining admixtures to increase freeze-thaw resistance. Although this is an advantage in compensating for the expansion of internal water, it is extremely deleterious when the concrete is exposed to abrasion. This appendix discusses procedures for obtaining high quality concrete and good construction practices in response to four causes of concrete deterioration (abrasion, chemical attack, corrosion, and freeze-thaw).

Certain guidelines should always be followed when designing a mix for use under water. A plastic mix of high workability should be used. This is important to prevent segregation and because mechanical compaction is difficult under water. These characteristics are achieved with a cement content of at least 350 kg/m3 and a slump of no more than 125 mm (24).

A low water-cement ratio is also desirable. This will produce high strength and low permeability. Permeability is reduced by reducing the amount of residual water left after hydration, which will cause voids, pores, and capillaries.

Prestressed concrete performs quite well in a hostile environment. This is because it is produced with dense, high strength concrete that is factory cured under a high degree of quality control. In addition, transverse cracks tend to automatically close because of the longitudinal prestressing force.

Adherence to good construction practices is always mandatory. Care in placing and compacting of the concrete mix and proper curing are all important. Strict compliance to plan dimensions and material specifications is essential. The use of epoxy coated bars and piles that have been treated before being driven is also recommended. In addition, a method was discovered for which a pile is soaked in clean water before it is driven so that the pile will not tend to soak up seawater after it is driven.

The following procedures are recommended in order to make concrete durable to the four specific causes of deterioration.

ABRASION

The most important concrete property for abrasion resistance is strength. The stronger the concrete is, the less erodable it will be. Concrete with 5,000 psi is twice as resistant as 3,000 psi. One very important concrete property affecting strength is the void to cement ratio which has been shown to vary inversely with abrasion resistance (25). Care should be taken, however, not to increase the cement content to the point where the homogeneity or the slump is impaired.

When selecting an aggregate, it is advantageous to select one that is at least as hard as the abrasive solids. In a case where sand is the abrasive, an extremely hard aggregate, such as quartz, should be used. Angular coarse aggregate exhibits significantly better abrasion resistance than round aggregate because it bonds more tightly to the cement paste. Only a minimum amount of fine aggregates should be used.

Calcium chloride can give concrete high abrasion resistance. Tests have shown that 2 percent calcium chloride accelerates the early strength of concrete. Samples have been produced that are, on the average, 100 percent more resistant to cavitation and 10-25 percent more resistant to abrasion. Any admixture that increases strength, such as water reducing agents, increases abrasion resistance (26).

When pouring concrete to resist abrasion, good construction practices are essential. Proper compaction and curing will help to provide a dense hard concrete. The shape of the substructure is also a factor. A streamline shape will help to avoid cavitation and reduce impact from moving solids.

CHEMICAL ATTACK

Cement properties, such as permeability and physical and chemical composition, play an important role in chemical resistance. In most cases, a good quality cement will be resistant to most chemicals; however, there are a few isolated cases where a concrete that is resistant to one type of attack may not be resistant to another. An example of this would be the tricalcium aluminate (C3A) content. In order for the concrete to resist chlorides, it must contain more than 8 percent C3A. On the other hand, in order for the concrete to resist sulfates, the content should not exceed 8 percent (27, 28). Permeability is the most important factor in resisting chemical attack because it affects the ability of the ions to penetrate the concrete. Authors vary on what is the ideal water-cement ratio. Most recommended ratios are from 0.45 to 0.55 for moderate and severe exposures respectively (29).

One of the most severe forms of chemical attack is due to sulfate ions. Sulfate ions attack tricalcium aluminate, a normal constituent of concrete. The product of this reaction expands and gives rise to cracks. A C3A content of 8 percent or less is required to minimize this action.

Seawater in the mix water has been demonstrated as a means to increase sulfate resistance. Doses up to 5 percent improve the 28 day strength also. This method is not recommended, however, because of the added risk of accelerated corrosion.

The proper choice of aggregate is important because it has an effect on porosity. Lightweight aggregates should be avoided because these aggregates are usually porous and allow passage of aggressive agents to the interior of the concrete. Hard impervious aggregate, such as quartz and solite, should be used whenever possible. Aggregates should always be clean and dry. Compatibility of the aggregates coefficient of expansion with that of the cement helps to reduce cracking, which, in turn, helps to prevent the ingress of aggressive agents.

Admixtures, such as pozzolans, have exhibited varied performances, depending on the type of attack. Fly ash, volcanic glass, diatomaceous earth, some shales, clay, and pumice are among the most common pozzolans. Pozzolans increase sulfate resistance by combining with free lime and by reducing porosity. This property is also advantageous in resisting acid attack. On the other hand, pozzolan cements are less resistant to magnesium attack because of the lack of free lime. Magnesium chloride in seawater reacts with calcium hydroxide (lime) to form magnesium hydroxide which is insoluable in water and seals the concrete. Without sufficient free lime, the concrete cannot be sealed. Air entraining also increases sulfate resistance.

Other cements, such as gypsum (supersulfated) cement, have performed well in the marine environment. High alumina cements also exhibit good durability in seawater. These cements are less porous than normal portland cements and contain no tricalcium aluminate. Type V (sulfate resisting) cement should be used in waters containing sulfates.

Chemical resistance is often difficult to achieve because more than one deleterious chemical may be present. In this instance, the required combination of concrete properties may be difficult to obtain. In any case, the good construction practices should always be observed.

CORROSION

The criteria for high quality concrete to protect reinforcing steel from corrosion are relatively the same as those to protect it from chemical attack. A dense impervious concrete is necessary to prevent corrosive agents from reaching the reinforcement. Again this is achieved by maintaining a low water-cement ratio and by the use of water-reducing admixtures to ensure compaction. Cement type, which has significant effect on chemical resistance, has no effect on corrosion resistance. A tricalcium aluminate content of greater than 8 percent, which is harmful in the presence of sulfates, is helpful in controlling chlorides. Tricalcium aluminate combines with chloride ions and takes them out of solution (27).

The use of seawater in the mix water, as mentioned before, for sulfate resistance is not recommended for reinforced concrete because the added chlorides will accelerate corrosion by combining with lime thereby lowering the alkalinity of concrete and making the concrete a better electrolyte. Aggregate should also be hard, clean, dry, and impervious. It should also be free from contamination. For example, if the aggregate was of marine origin, chlorides could be present. Admixtures and corrosion inhibitors have proved useful in preventing corrosion of reinforcement. Certain inhibitors have had deleterious effects on concrete properties. Some are subject to leaching and can establish concentration cells enhancing corrosion. Others can seriously affect the concrete. Corrosion inhibitors are a fairly new concept and require more research.

Admixtures, such as pozzolans, are often times beneficial in inhibiting corrosion. Fly ash exhibits good corrosion resistance by increasing the energy required to cause corrosion. Most pozzolans reduce the alkalinity of concrete, which makes the steel more susceptible to corrosion; but it also reduces the permeability, which makes the steel less vulnerable.

By employing the proper procedures when preparing concrete, a durable concrete will result that will protect the reinforcing steel. Most steel corrosion is the result of poor construction practices. Insufficient cover and a variety of other conditions will all cause accelerated corrosion of the reinforcing steel.

FREEZE-THAW

The physical and chemical properties of freeze-thaw resistant concrete are extremely important. Many times, even good quality concrete will deteriorate because of freeze-thaw. Concrete is especially susceptible when completely saturated. Therefore, special care and techniques must be used to produce a concrete that is dense, impervious, and difficult to saturate.

The method for obtaining a dense impervious concrete is, more or less, the same as that mentioned previously for other forms of attack. A low water-cement ratio reduces capillary size and continuity, thus reducing the permeability of the concrete. Reduced capillary size also lowers the freezing point of pore water due to surface and thermodynamic forces. A water-cement ratio of 0.40 to 0.45 is recommended. In moderate climates this ratio can be raised slightly to 0.50 to 0.55. A low tricalcium aluminate content also helps to produce a more dense concrete (30, 31, 32).

The type of aggregate used is also significant in freeze-thaw resistant concrete. The aggregate should be nonporous and dry. Nonporous aggregates are less likely to become saturated at a later date. Dry aggregates are needed to ensure that the aggregate is not saturated when placed; however, when properly cured, saturated aggregate is not usually a problem. This is because of self-desication during early hydration. Transpiration also helps to keep the aggregate dry by allowing water to automatically migrate from a wet to a dry area. Most freezing and thawing occurs in the splash zone where transpiration will be a factor. Aggregate size has a great effect on frost resistance. Large aggregates cause excess expansion during freezing. Coefficients of expansion can also cause problems if the aggregates and the cement paste expand at different rates.

Certain admixtures have been useful in resisting the effects of freeze-thaw. The most common are air-entraining admixtures. Air entrainment provides added space for water to migrate during freezing. Too much entrained air can lower the strength, however. Strength reduction in most cases rarely exceeds 15 percent (33). Most of the effects of air entrainment are advantageous. Freeze-thaw durability, workability, lower water content, and less segregation are among a few. Three air entraining admixtures in extensive use are: wood resin, detergents, and sulfonated hydrocarbons of petroleum. These admixtures should be administered in doses that provide about 4 1/2 percent air by volume (34). The American Concrete Institute suggests air contents from 3 percent to 7 1/2 percent, depending on the severity of exposure and normal aggregate size. Air content alone is not enough to resist freeze-thaw damage. Void spacing is also important. If voids are too far apart, the water will not be able to migrate to the voids. Authors recommend void spacings between 0.005 in. and 0.008 in. (28, 35, 36).

Silicone admixtures have shown promise in combating freeze-thaw. Silicones increase the freeze-thaw durability greatly and at the same time increase the concrete strength. Water-reducing admixtures reduce the capillary size and porosity, thus yielding a more durable concrete.

Porous particle admixtures have been used experimentally with promising results. Porous particles with at least 30 percent total porosity and pore diameters between 0.3 and 2 microns have significantly increased freeze-thaw resistance. Commercially fired clay-brick and diatomaceous earths show the most promise; however, diatomaceous earths can cause alkali-silica reactions and should be used with caution. Porous particles have advantages over air-entrainment because the control of air-entrainment over narrow limits is difficult. The amount and spacing of entrained air are dependent on many factors, such as mix composition, temperature, and time taken during mixing and finishing operations. When using porous particles, spacing is easily controlled by particle size and concentration. The limiting size of particles should be between 0.4 and 0.8 mm due to the pore structure of the brick. Beyond this point, the internal pore volume is insufficient (37).

The effects of freeze-thaw can be reduced, but they are very difficult to eliminate. Any concrete can be damaged when it is completely saturated. Cyclic freezing and thawing will inevitably cause microcracks and strength reductions in concrete.

Appendix D

CONCRETE DETERIORATION

INITIATION STAGE

Abrasion

1. Slow at first due to smooth hard surface
2. Cavitation produces water hammer
3. Waterline abrasion due to grinding of ice sheets
4. Mudline abrasion
   a. Due to rolling or impacting solids
   b. Tension stresses due to turbulent underpressure.

Freeze-Thaw

Water level falls and water on outside surface of concrete freezes. Then water level rises and ice on outside surface of concrete thaws.

PROPAGATION STAGE

Abrasion

1. Deterioration is faster in this stage due to:
   a. A rougher surface texture
   b. Exposure of softer interior concrete
2. Ice sheets abrade cover.

Freeze-Thaw

Freezing of water in concrete pores causes internal pressure. Theories to explain scaling from freeze-thaw are as follows:

1. Pressure developed by expulsion of water from saturated aggregate particles
2. Hydraulic pressure developed in capillaries just below the concrete surface.
3. Accretion of moisture to ice crystals in capillaries below the surface
4. Osmotic pressures caused by concentration of salt in capillaries immediately beneath the concrete surface
5. Cracking and crazing provide channels for moisture to reach underlying capillary ice
6. Cyclic temperature fluctuations cause creep, fatigue, and differential expansion of aggregate and mortar.

Carbonic Acids

1. Carbonic acids react with calcium hydroxide to form calcium carbonate and take twice as much moisture. $[CO_2 + H_2O \rightarrow H_2CO_3]$ + $Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$
2. Additional free moisture may migrate into the concrete depending on the concrete ambiency
3. Acids reduce alkalinity, not necessarily strength
4. Reduces passivity of steel.

Sulfates

1. Attacks free lime to form calcium sulfate (gypsum) which occupies twice the initial volume
2. Gypsum and hydrated calcium aluminate form calcium
3. Ettringite attracts a large number of water molecules causing further expansion
4. Expansive forces cause cracking.

Magnesium Sulfate

1. Magnesium sulfate attacks hydrated aluminum to form ettringite, but also attacks hydrated silicates to form gypsum, nearly insoluable magnesium hydroxide and silica gel.
2. Ettringite that is formed is unstable in magnesium sulfate and forms more gypsum.

Magnesium Chloride

1. Magnesium chloride reacts with calcium hydroxide as follows: $MgCl_2 + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaCl_2$
2. $CaCl_2$ is readily soluable and is easily leached
3. $Mg(OH)_2$ precipitates and seals concrete slowing corrosion.

Chlorides

1. Chlorides reduce alkalinity of the concrete paste and reduce passivity of steel
2. Chlorides tend to make the concrete a better electrolyte promoting the corrosion of the reinforcement.

Ammonium Ions

1. React with calcium
2. Reduce strength of concrete

Corrosion

1. Corrosion begins slowly
2. Corrosion products actually inhibit corrosion
3. Corrosion products expand and crack cover.

Appendix E

CASE HISTORY WORK SHEETS

A. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1 Deficiency ABRASION

2. Method of repair PONDING (SEE FIGURE 6) Date 1961

3. Substructure construction COLUMN BENT Date 1961

4. Environment FRESH WATER

5. Location US 90 OVER BOISE RIVER

6. Owner IDAHO DEPARTMENT OF HIGHWAYS

7. Owner evaluation Date 8-6-81

a. Struct'l Integrity Restored? NO b Deter Arrested? NO

c. Cause Eliminated? NO d Life or anticipated life of methods SHORT

e Owners evaluation UNANTICIPATED STREAMBED DEPOSITS FORMED ISLAND WHICH REDIRECTED STREAM FLOW. POTENTIAL FOR SCOUR NOW EXISTS.

8. Researcher's comments DOWNSTREAM BRIDGE WITHOUT PONDING SHOWS NO INDICATION OF SCOUR.

B. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of Repair EPOXY COATING (SEE FIG. 7) Date UNKNOWN
3. Substructure construction PILE BENT Date 1932
4. Environment BRACKISH WATER (10 PPT)
5. Location ROUTE 11 OVER LAKE PONCHARTRAIN
6. Owner LOUISIANA DEPARTMENT OF HIGHWAYS
7. Owner evaluation Date 10-6-81
   a. Struct'l Integrity Restored? NO b Deter Arrested? NO
   c Cause Eliminated? NO d. Life or anticipated life of methods 1 YEAR
   e Owners evaluation ALL APPLICATIONS HAVE FAILED. STRAIGHT EPOXY IS USELESS.
8. Researcher's comments CONTROL IS HARD TO OBTAIN IN THE FIELD.

C. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of repair PVC PILE WRAP (SEE FIG 8) Date UNKNOWN
3. Substructure construction PILE BENT Date 1932
4. Environment BRACKISH WATER (10PPT)
5. Location ROUTE 11 OVER LAKE PONCHARTRAIN
6. Owner LOUISIANA DEPARTMENT OF HIGHWAYS
7. Owner evaluation Date 10-6-81
   a. Struct'l Integrity Restored? NO b Deter Arrested? YES
   c. Cause Eliminated? NO d Life or anticipated life of methods EXTENDED
   e. Owners evaluation APPEARS TO BE A VIABLE REPAIR METHOD.
8. Researcher's comments USEFULLNESS IN AREAS WITH ICE PROBLEMS IS DOUBTFUL.

D. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of Repair FABRIC JACKET (SEE FIGURE 9) Date MID 1970'S
3. Substructure construction PILE BENT Date 1932
4. Environment BRACKISH WATER (10PPT)
5. Location ROUTE 11 OVER LAKE PONCHARTRAIN
6. Owner LOUISIANA DEPARTMENT OF HIGHWAYS
7. Owner evaluation Date 10-6-81
   a. Struct'l Integrity Restored? YES b. Deter Arrested? APPARENTLY
   c Cause Eliminated? NO d Life or anticipated life of methods EXTENDED
   e Owners evaluation UNSIGHTLY WITH ROPES USED DURING CONSTRUCTION LEFT IN PLACE.
8. Researcher's comments

E. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of repair RIGID JACKET-EPOXY FILLED (FIG 10) Date UNKNOWN
3. Substructure construction PILE BENT Date 1932
4. Environment BRACKISH WATER (10 PPT)
5. Location ROUTE 11 OVER LAKE PONCHARTRAIN
6. Owner LOUISIANA DEPARTMENT OF HIGHWAYS
7. Owner evaluation Date 10-6-81
   a. Struct'l Integrity Restored? NO b Deter Arrested? SEE BELOW.
   c. Cause Eliminated? YES d. Life or anticipated life of methods EXTENDED
   e Owners evaluation GUARDED OPTIMISM. SEEMS TO BE HOLDING UP VERY WELL. OWNER QUESTIONS IF DETERIORATION IS CONTINUING UNDER JACKET.
8. Researcher's comments THE NEXT CASE HISTORY WAS NOT SO SUCCESSFUL DUE TO ICE.

F. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency ICE ABRASION AND FREEZE-THAW DAMAGE
2. Method of Repair RIGID JACKET - EPOXY FILLED (FIGS 11&12) Date UNKNOWN
3. Substructure construction PILE BENT Date UNKNOWN
4. Environment BRACKISH WATER - ICE IN WINTER
5. Location US 50 OVER NANTICOKE RIVER NEAR VIENNA, MD.
6. Owner MARYLAND DEPARTMENT OF TRANSPORTATION
7. Owner evaluation Date 9-15-81
   a. Struct'l Integrity Restored? NO b. Deter. Arrested? NO
   c. Cause Eliminated? NO d. Life or anticipated life of methods LIMITED
   e. Owners evaluation DETERIORATION WAS ONLY HIDDEN. 25% FAILURE RATE.
8. Researcher's comments GROUT DID NOT BOND TO FORM. WATER INTRUDED. ICE LENSES CAUSED FAILURE OF SEAMS.

G. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of repair RIGID JACKET-GROUT FILLED-EPOXY SEALED Date MID 1970's
3. Substructure construction PILE BENT Date 1932
4. Environment BRACKISH WATER (10 PPT)
5. Location ROUTE 11 OVER LAKE PONCHARTRAIN
6. Owner LOUISIANA DEPARTMENT OF HIGHWAYS
7. Owner evaluation Date 10-6-81
   a. Struct'l Integrity Restored? YES b Deter. Arrested? APPARENTLY
   c. Cause Eliminated? NO d. Life or anticipated life of methods UNKNOWN
   e Owners evaluation LOOKS GOOD AT PRESENT. BUT WHETHER OR NOT DETERIORATION IS STOPPED OR MERELY HIDDEN REMAINS TO BE SEEN.
8. Researcher's comments THE USE OF CONVENTIONAL (PEA GRAVEL GROUT) MATERIALS SEEMS TO PROVIDE CONSISTENT RESULTS WITH LESS DIFFICULTY.

H. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS IN SPLASH ZONE
2. Method of Repair SQUARE RIGID JACKET - EPOXY MORTAR Date MID 1970's
3. Substructure construction PILE BENT Date 1930's
4. Environment BRACKISH WATER
5. Location BAYOU CHICO BRIDGE
6. Owner FLORIDA DEPARTMENT OF TRANSPORTATION
7. Owner evaluation Date 10-7-81
   a. Struct'l Integrity Restored? YES b. Deter Arrested? APPARENTLY
   c. Cause Eliminated? NO d. Life or anticipated life of methods UNK.
   e. Owners evaluation APPEARS TO BE HOLDING UP WELL. CORROSION MAY BE CONTINUING BUT AT A LESSER DEGREE.
8. Researcher's comments REPAIR METHOD IS SATISFACTORY. NOT POSSIBLE TO DETERMINE IF DETERIORATION WAS ARRESTED.

I. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS - LOSS OF COVER
2. Method of repair C.M JACKET - CONCRETE FILLED (FIG 15) Date 1960's
3. Substructure construction PILE BENT Date 1930's
4. Environment BRACKISH WATER, ICE IN WINTER
5. Location ROUTE 6 OVER WAREHAM RIVER
6. Owner MASSACHUSETTS DEPARTMENT OF PUBLIC WORKS
7. Owner evaluation Date 8-25-81
   a. Struct'l Integrity Restored? YES b Deter Arrested? APPARENTLY
   c Cause Eliminated? YES d. Life or anticipated life of methods 20 YRS
   e Owners evaluation SATISFACTORY REPAIR ALTHOUGH DAMAGE IS NOW OCCURING ABOVE THE JACKETS.
8. Researcher's comments GALVANIZED METAL AFFORDS GOOD PROTECTION AGAINST ICE.

J. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency ABRASION - LOSS OF CONCRETE SECTION
2. Method of Repair METAL JACKET - CONC. FILLED (NC 16) Date LATE 1970's
3. Substructure construction 8FT DIAMETER COLUMN Date LATE 1960's
4. Environment FAST FLOWING FRESH WATER
5. Location SOUTH UMPQUA RIVER
6. Owner OREGON HIGHWAY DIVISION
7. Owner evaluation Date 8-3-81
   a. Struct'l Integrity Restored? YES b Deter Arrested? YES
   c Cause Eliminated? NO d. Life or anticipated life of methods 25 YRS
   e Owners evaluation SATISFACTORY - INCREASED DIAMETER OF COLUMN BY ONE FOOT.
8. Researcher's comments JACKET WAS REMOVED EVEN THOUGH IT WOULD HAVE PROVIDED ADDITIONAL PROTECTION.

K. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency CORROSION OF REBARS - LOSS OF COVER
2. Method of repair WROUGHT IRON JACKET Date 1956
3. Substructure construction PILE BENT Date 1930
4. Environment BRACKISH WATER
5. Location ROUTE 6 OVER WAREHAM RIVER
6. Owner MASSACHUSETTS DEPARTMENT OF PUBLIC WORKS
7. Owner evaluation Date 8-25-81
   a. Struct'l Integrity Restored? YES b Deter. Arrested? NO
   c. Cause Eliminated? NO d Life or anticipated life of methods 25 YRS
   e Owners evaluation SERIOUS DETERIORATION NOW OCCURING ABOVE JACKETS. WROUGHT IRON IS SUBJECT TO CORROSION, BUT JACKETS LASTED FAIRLY WELL.
8. Researcher's comments AN OLDER REPAIR METHOD. METAL JACKETS GOOD IN ICE AREAS.

L. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency ABRASION & CHEMICAL ATTACK LOSS OF CONCRETE
2. Method of Repair SHEET PILING - CONC. BACKFILL Date EARLY 1970's
3. Substructure construction MASS PIER ON PILES Date 1930's
4. Environment BRACKISH WATER
5. Location BAYOU CHICO BRIDGE
6. Owner FLORIDA DEPARTMENT OF TRANSPORTATION
7. Owner evaluation Date 10-7-81
   a. Struct'l Integrity Restored? YES b. Deter Arrested? YES
   c Cause Eliminated? NO d. Life or anticipated life of methods 20 YRS
   e Owners evaluation EFFECTIVE THOUGH COSTLY
8. Researcher's comments A WELL ESTABLISHED METHOD FOR MASS PIERS THAT SUBSTANTIALLY EXTENDS LIFE.

M. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1. Deficiency ICE ABRASION OF FOOTING
2. Method of repair SHEET PILING - TREMIE BACKFILL Date MID 1970's
3. Substructure construction MASS CONC. ON PILES Date MID 1930's
4. Environment SWIFT FLOWING BRACKISH WATER
5. Location SWIFT'S RIVER, WAREHAM
6. Owner MASSACHUSETTS DEPARTMENT OF PUBLIC WORKS
7. Owner evaluation Date 8-25-81
   a. Struct'l Integrity Restored? YES b. Deter. Arrested? YES
   c. Cause Eliminated? NO d Life or anticipated life of methods 20 YRS
   e Owners evaluation SATISFACTORY
8. Researcher's comments SHEETING PROTECTS CONCRETE WHILE IT IS NEW.

N. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1\. Deficiency: ICE ABRASION AND FREEZE-THAW DAMAGE

2\. Method of Repair: CONC. COLLAR (SEE FIGS 17 & 18) Date: UNKNOWN

3\. Substructure construction: PILE BENT Date: UNKNOWN

4\. Environment: BRACKISH WATER - ICE IN WINTER

5\. Location: US 50 OVER CHOPTANK RIVER

6\. Owner: MARYLAND DEPARTMENT OF TRANSPORTATION

7\. Owner evaluation Date: 9-15-81

- a. Struct'l Integrity Restored? NO b Deter. Arrested? YES
- c. Cause Eliminated? NO d. Life or anticipated life of methods: 10 YEARS
- e Owners evaluation: IT SAVED THIS BRIDGE FROM SEVERE DAMAGE.

8\. Researcher's comments: COLLAR MUST BE REPLACED PERIODICALLY.

O. METHODS TO ARREST DETERIORATION - CASE HISTORY WORK SHEET

1\. Deficiency: CORROSION OF REBARS IN SPLASH ZONE

2\. Method of repair: GUN APPLIED MORTAR (FIGS 19 & 20) Date: UNKNOWN

3\. Substructure construction: PILE BENT Date: 1932

4\. Environment: BRACKISH WATER (10 PPT)

5\. Location: ROUTE 11 OVER LAKE PONCHARTRAIN

6\. Owner: LOUISIANA DEPARTMENT OF HIGHWAYS

7\. Owner evaluation Date: 10-6-81

- a. Struct'l Integrity Restored? NO b Deter Arrested? NO
- c. Cause Eliminated? NO d Life or anticipated life of methods: SHORT
- e Owners evaluation: MARGINAL SUCCESS IF AT ALL.

8\. Researcher's comments: DETERIORATION FREQUENTLY OCCURS AT INTERFACE OF MORTAR AND THE EXISTING CONCRETE.

Appendix F SUBSTRUCTURE ANALYSIS

BYRD, TALLAMY, MACDONALD & LEWIS
Consulting Engineers
Falls Church, Virginia

PROJECT: APPENDIX F
SUBJECT: SUBSTRUCTURE ANALYSIS EXAMPLE
Made by ______ Date ______
Checked by ______ Date ______
Sheet No 1 of 1

LIMITS OF DECAY

CAPACITY OF BRIDGE = 3 TONS MIN

LIVE LOAD REACTION ON PILE =

$$\frac{3\text{ TONS}}{15^{T}\text{ TRUCK}} \times 13.6^{K}/\text{WHEEL LINE} \times \underset{\text{INFLUENCE}}{1.4075} = 3.83^{K}$$

DEAD LOAD REACTION ON PILE $= 0.3(6)1.1 = 1.98^{K}$

AREA REQUIRED FOR COMPRESSION

$$A = (3.83^{K} + 1.98)/1100\text{ KSI}\ \alpha = \underline{8.80\text{ IN}^2}$$, WHERE α = 60% REDUCTION FACTOR

BUCKLING :

$$\frac{P}{A} = \frac{P}{\pi R^2} = \frac{4.813\,E\alpha}{(L/R_2)^2}$$, REARRANGING

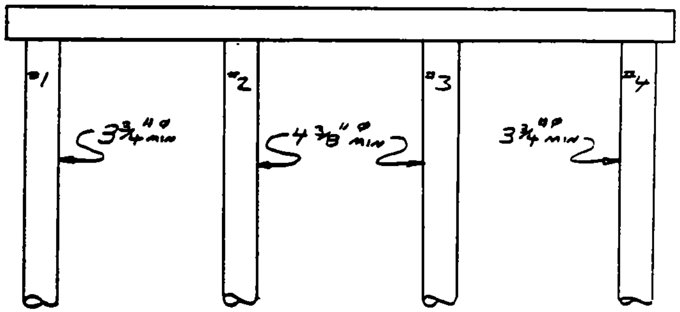
$$R^4 = \frac{4PL^2}{4.813\,\pi E\alpha} = \frac{4(3.83+1.98)120^2}{4.813\,\pi\,1.7\times10^3(.6)} = 21.7\text{ in}^4$$

$R = 2.158$ in

$\underline{\text{AREA} = 14.63\text{ in}^2} > 8.8\text{ in}^2$

LIMIT OF DECAY

DIAMETER OF PILE $= 2R = 4.3$ in OR $4\frac{3}{8}''$



BYRD, TALLAMY, MACDONALD & LEWIS

ANALYSIS OF PILE

Bridge No APPENDIX F 1/3
County SUBSTRUCTURE ANALYSIS
Made by ____ Date ____
Checked by ____ Date ____

Pile Spacing (L) = 6'-0" Number of Piles + 4 Skew 0°

Pile Size 12' ϕ ☐ Abutment (End Bent) - Span Length ____

Beam Spacing 2'-0" ☒ Intermediate Bent-Span Length 30.0' & 30.0'

Dead Load Reaction/Beam (D.L./BEAM) 0.25 + 0.25 = 0.50 (See Note 4)

Live Load Reaction (L L) for H Truck (from chart) = 13.6^k (See Notes 1, 2 & 3)

D.L. Continuity Distribution Factor = 1.10

L L. Continuity Distribution Factor + 1.4075 (See Note 5)

D.L Reaction = $\left[\frac{\text{(D.L /Beam) x (Cos Skew)*}}{\text{Beam Spacing}} + \text{Wt Cap/LF}\right]$ x L x (D L. Cont. Dist Fact.) 1.98^k

L L. Reaction = (L L.) x (L.L. Cont Dist. Fact.) = 19.14^k

Capacity (INVENTORY) = } BUCKLING OR BEARING 48.0^k

Capacity (OPERATING) = } 65.4^k

Capacity Available for L.L = (Capacity Inventory) - (D L Reaction) = 46.02^k INV

Capacity Available for L L = (Capacity Operating) - (D.L Reaction) = 63.42^k OPER

Capacity Factor = (Capacity Avail L.L.) + (L.L. Reaction) 2.404 INVENTORY

3.313 OPERATING

Ration = (capacity Factor Operating) + (Capacity Factor Inventory) 1.38

RATINGS

	INVENTORY	RATIO	OPERATING
H Truck - INV F x 15 =	36.06 TONS	1.38	49.76 TONS

NOTES

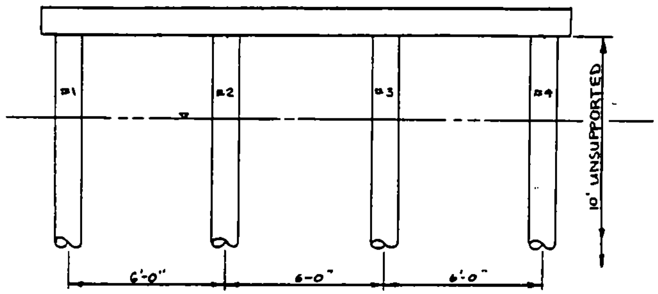
1. If the cap is of any other material than timber, multiply liveload by impact factor
2. L L. H Truck from AASHTO.
3. For unequal longitudinal spans, L.L. reaction to be average of intermediate reaction for the two considered spans, but not less than end reaction for larger span
4. D.L./Beam to be for BOTH SPANS FOR INTERIOR CAP
5. If the cap simply supported with a splice, do not use continuity factors for D L. and L L.

* Skew is 0° when cap is perpendicular to roadway centerline. Therefore COS = 1.

BYRD, TALLAMY, MACDONALD & LEWIS
Consulting Engineers
Falls Church, Virginia

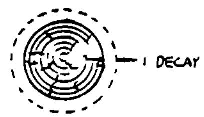
PROJECT APPENDIX F
SUBJECT SUBSTRUCTURE ANALYSIS EXAMPLE
Made by ____ Date ____
Checked by ____ Date ____
Sheet No 2 of 3

BENT SKETCH + CONDITION



SPANS = 30'-0" EQUAL
AASHTO WHEEL SPACING = 6'-0
MIN SPACING BETWEEN TRUCKS = 3'-0'
TIMPER CAP 12"x12"
ALL TIMBER PILES 12"ϕ
F_c = 1100 PSI INV, 1463 OPER
E = 1.7x10⁶ PSI

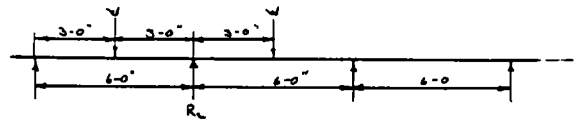
GENERAL CONDITION OF PILE #2



INFLUENCE COEFFICIENT CALCULATION

ALL COEFFICIENTS ARE FROM . ANGER, GEORG TEN DIVISION INFLUENCE LINES FOR CONTINUOUS BEAMS TABLE 1.1.1

CASE #1



$\frac{3}{6}$ = 0.5 ⇒ 0.7250

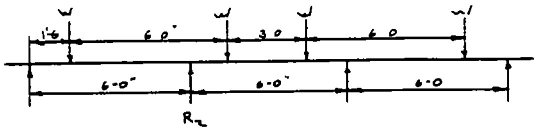
$\frac{9}{6}$ = 1.5 ⇒ 0.5750

1.3000 = INFLUENCE COEFFICIENT (ONE TRUCK)

BYRD, TALLAMY, MACDONALD & LEWIS
Consulting Engineers
Falls Church, Virginia

PROJECT Appendix F
SUBJECT Substructure Analysis Example

Made by ______ Date ______
Checked by ______ Date ______
Sheet No. 3 of 3



$\frac{1\ 5}{6} = 0\ 25 \rightarrow 0\ 3895$

$\frac{7\ 5}{6} = 1\ 25 \rightarrow 0\ 8505$

$\frac{10\ 5}{6} = 1\ 75 \rightarrow 0\ 2605$

$\frac{16\ 5}{6} = 2.75 \rightarrow -0\ 0930$

1 4075 ← INFLUENCE COEFFICIENT (TWO TRUCKS) CONTROLS

CAPACITY

RADIUS OF GYRATION = $\frac{r}{2} = \frac{5}{2} = 2\ 5\ \text{IN}^2$

BUCKLING ALLOWABLE $P/A = \frac{4\ 813\ E}{(l/r)^2} = \frac{4\ 813(1.7\times10^6)}{(120/2.5)^2} = 3551$ PSI

COMPRESSION ALLOWABLE STRESS BY AASHTO = 1100 PSI ← CONTROLS

AREA REMAINING = $5^2 \times \pi = 78\ 54\ \text{IN}^2$

$$\left.\begin{aligned} \text{CAPACITY} &= \frac{78\ 54\ \text{IN}^2 \times 1100\ \text{lb}/\text{IN}^2}{2000\ \text{lb}/\text{TON}} = \underline{86.4\ \text{TONS INV}} \\ &\qquad \times 1\ 33 \\ &\qquad = \underline{144\ 7\ \text{TONS OPER.}} \end{aligned}\right\} \text{COMPRESSION}$$

HOWEVER

BEARING MAX. CAPACITY FOR A 12' PILE = 24 TONS INV
= 32.7 TONS OPER ← CONTROLS

Appendix G

PROPOSED GUIDELINE BOOKLET

TABLE OF CONTENTS

INTRODUCTION

The number of different types of substructure elements and the types of deficiencies which occur to them are relatively limited. There is, however, a wide diversity of opinion on how the significance of a deficiency should be judged. Most jurisdictions responsible for the underwater inspection and repair of bridge substructure elements. have developed their own subjective "rule of thumb" guidelines for the rating of a deficiency which may or may not be written in any appreciable detail. These "rule of thumb" guidelines may often appear arbitrary, but they are of substantial significance as they are generally based on the judgement of experienced bridge engineers. The purpose of this booklet is to provide a guided, objective method to measure the threat to the integrity of a structure from a maintenance viewpoint. This booklet is <u>not</u> to be construed as a replacement for the rating system now used to rate the substructure condition for Item 60 of the Federal Highway Administration's (FHWA) "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (SI&A), but rather as an adjunct to it. The SI&A rating system is required for consistency of approach for funding eligibility from a reconstruction viewpoint. The methods presented herein are only meant to provide a more consistent approach to the process of assessing deficiencies from a maintenance viewpoint.

The guidelines and modifications presented herein aid inspection personnel in arriving at an initial assessment of a deficiency expressed as a numerical value. This assessment, in turn, indicates the urgency of corrective action. This number prescribes the type of action to be taken in the inspection process as well as by maintenance forces in scheduling work which is to be performed.

INSTRUCTIONS

On the following pages there are a number of guidelines for types of substructure elements and materials describing various states of deterioration. The steps to be taken in the use of these guidelines are presented below.

1) Inspection personnel are to select the description which most closely depicts the severest example of deterioration found. The number appearing adjacent to the chosen description is the initial assessment of the deterioration. 2) The deficiency should then be photographed or sketched for the purpose of documentation in the inspection report. 3) The initial assessment may then be modified based on the threat to the integrity of the structure caused by the effect of supplemental or external factors. In this way, deficiencies may first be evaluated by the guidelines shown and then modified by conditions which are unique to a particular area or climate. The right hand chart provided on the back of each form is to be used to perform this function for all deficiencies. 4) The assessment modification should then be algebraically added to the initial assessment to produce the maintenance urgency index. Assessment and modification numbers may be circled to highlight the guidelines used. The statement next to the numbers chosen should be underlined to document the reason for the selection. 5) Once an urgency index has been selected, the type of action to be taken in inspection process and by maintenance forces can then be selected. This is done by consulting the chart on the next page. The Administrative level at which the assessment modification should be approved is not addressed here.

With the aid of this method, the assessment of underwater deficiencies of bridge substructures can be performed in an objective manner. Inspection personnel can uniformly arrive at a numerical value to indicate the urgency of corrective action from a maintenance viewpoint.

SUBSTRUCTURE CONDITION
BELOW THE WATERLINE
URGENCY OF CORRECTIVE ACTION

MAINTENANCE URGENCY INDEX

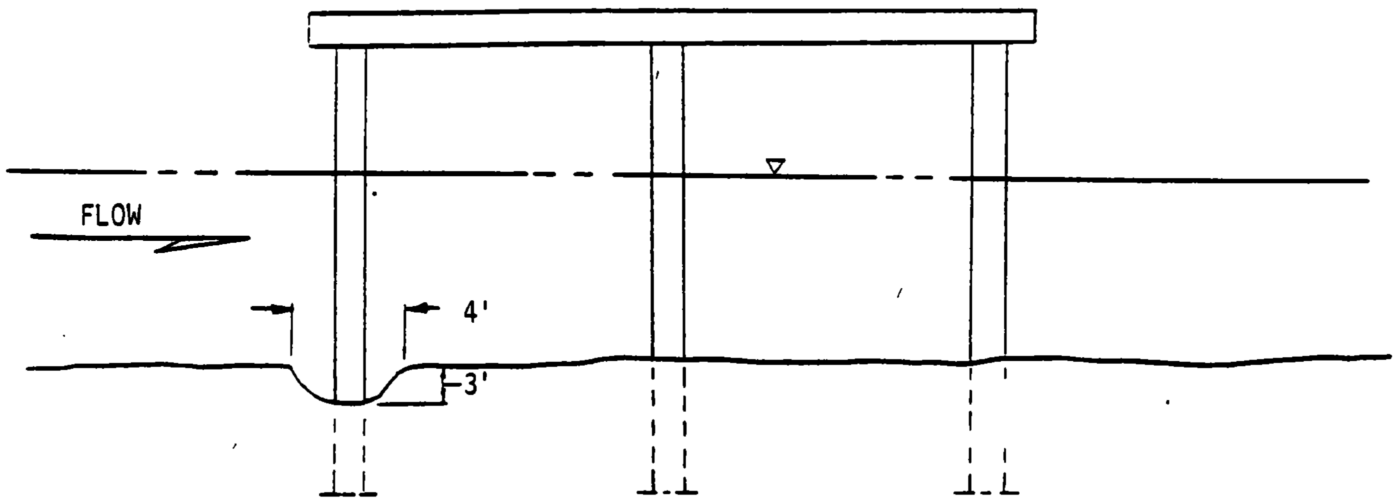
Maintenance Urgency Index	Maintenance Immediacy of Action	Inspection Course of Action
9	No repairs needed.	Note in inspection report only.
8	No repairs needed. List specific items for special inspection during next regular inspection.	
7	No immediate plans for repair. Examine possibility of increased level of inspection.	
6	By end of next season - add to scheduled work.	
5	Place in current schedule - current season - first reasonable opportunity.	Special notification to superior is warranted.
4	Priority - current season - review work plan for relative priority - adjust schedule if possible.	
3	High priority - current season as soon as can be scheduled.	
2	Highest priority - discontinue other work if required - emergency basis or emergency subsidiary actions if needed (post, one lane traffic, no trucks, reduced speed, etc.)	Notify superiors verbally as soon as possible and confirm in writing.
1	Emergency actions required - reroute traffic and close.	
0	Facility is closed for repairs	

Assessment Modification Chart Based on Threat to Integrity of Structure

Modification	Description
+2	No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is slowing; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect.* (Note: May be used for original rating of 2 to 6 inclusive.)
+1	No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect.* (Note: May be used for original rating of 2 to 7 inclusive.)
0	No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)
-1	Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)
-2	Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)

* Structural effect includes redundancy of load path and other factors.

SCOUR AROUND PILES



$\overline{\text{Initial}} \pm \overline{\text{Modification}} = \overline{\text{Urgency}}$

Initial Assessment ± Modification = Urgency Index

DESCRIPTION:______________________________

____

____

____

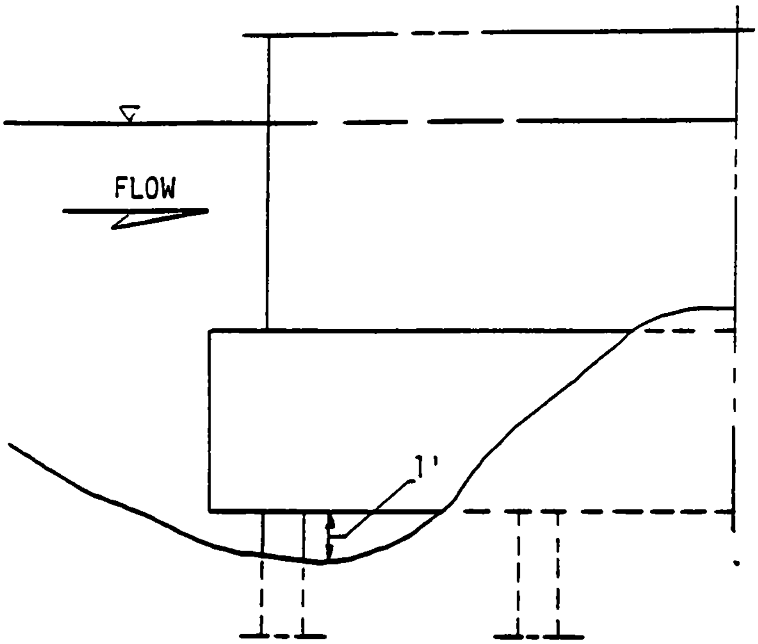
____

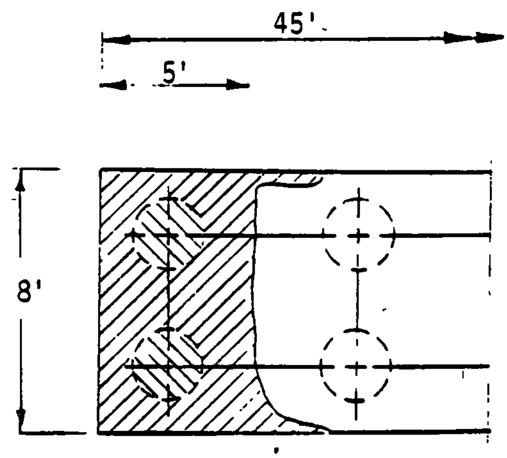
SKETCHES:

GUIDELINES	Initial Assessment
No scour	9
No scour	8
Light scour around piles	7
Moderate scour around piles	6
Moderately heavy scour pockets around piles	5
Heavy scour pockets around piles	4
Scour pockets have increased unsupported length dramatically	3
Pile is completely exposed	2
Structure is threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing, 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

UNDERMINING OF FOOTING





_______ ± _______ = _______
Initial Assessment ± Modification = Urgency Index

DESCRIPTION:____

____

____

____

____

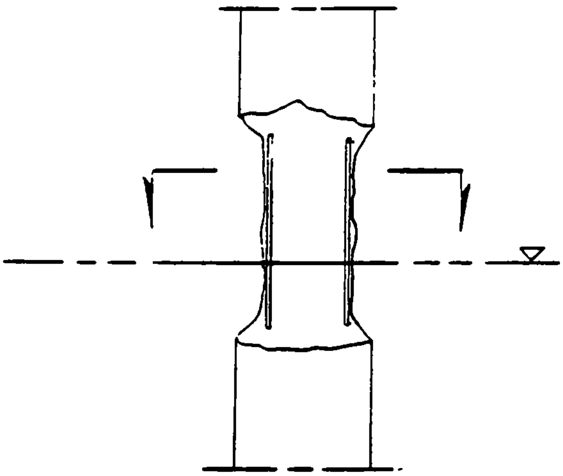
SKETCHES:

Note: Once a pile is exposed, it must also be rated

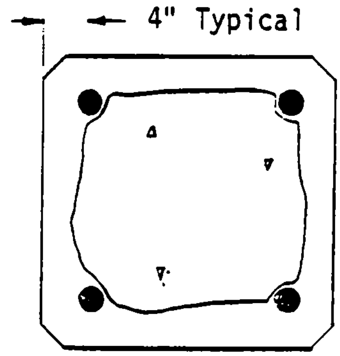
GUIDELINES	Initial Assessment
No undermining	9
No undermining	8
0% to 10% of pile footing area is exposed	7
10% to 30% of pile footing area is exposed	6
Greater than 30% of pile footing area is exposed. 0% to 10% of piles are exposed.	5
10% to 50% of piles are exposed	4
50% to 90% of piles are exposed. 0% to 100% of spread footing is undermined.	3
90% to 100% of piles are exposed	2
Structure threatened	1
Structure is closed.	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate, 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

SECTION LOSS OF CONCRETE PILE



ELEVATION



SECTION

________ ± ________ = ________

Initial Assessment | Modification | Urgency Index

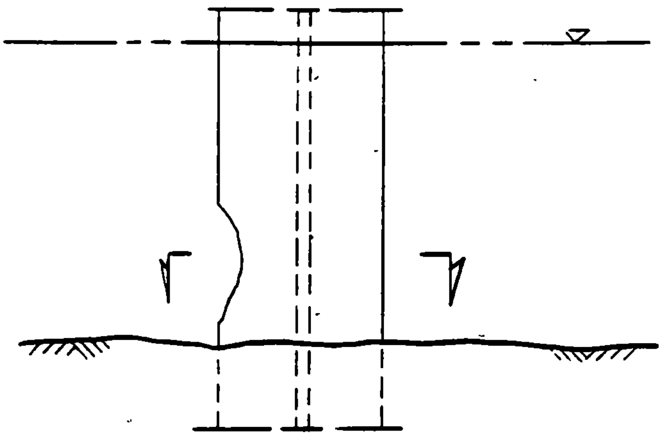
DESCRIPTION: ____

SKETCHES:

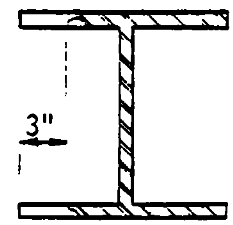
GUIDELINES	Initial Assessment
0% section loss - area in plan	9
0% section loss - area in plan	8
0% to 5% section loss - area in plan	7
5% to 10% section loss - area in plan	6
10% to 15% section loss - area in plan or Reinforcing bar has section loss.	5
15% to 20% section loss - area in plan or Reinforcing bar has section loss	4
20% to 30% section loss - area in plan or Reinforcing bar is free-standing	3
Over 30% section loss - area in plan	2
Structure is threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate, 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate, 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly, 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

SECTION LOSS OF STEEL PILE



ELEVATION



HP 10 x 42
SECTION

$\overline{\text{Initial Assessment}} \pm \overline{\text{Modification}} = \overline{\text{Urgency Index}}$

DESCRIPTION: ____

____

____

____

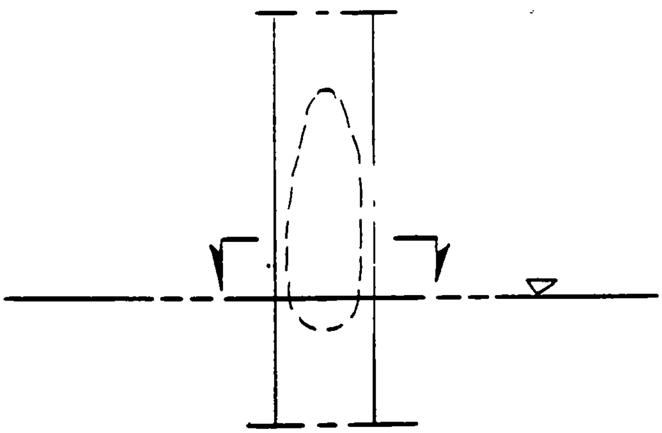
____

SKETCHES:

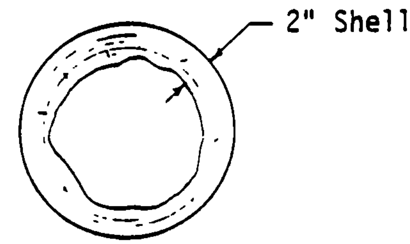
GUIDELINES	Initial Assessment
0% section loss - area in plan	9
0% section loss - area in plan	8
0% to 5% section loss - area in plan	7
5% to 15% section loss - area in plan	6
15% to 35% section loss - area in plan	5
35% to 50% section loss - area in plan	4
50% to 70% section loss - area in plan	3
More than 70% section loss - area in plan	2
Structure threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable, 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

SECTION LOSS OF TIMBER PILE



ELEVATION



SECTION

_____ Initital Assessment ± _____ Modification = _____ Urgency Index

DESCRIPTION: ____

____

____

____

SKETCHES:

GUIDELINES	Initial Assessment
0% section loss in plan (external)	9
0% section loss in plan (external)	8
0% to 5% section loss in plan (external)	7
5% to 15% section loss in plan (external)	6
15% to 25% section loss in plan (external)	5
25% to 50% section loss in plan (external), or 0% to 10% section loss in plan (internal), or 0% to 10% section loss in plan (internal + external)	4
50% to 75% section loss in plan (external), or 10% to 50% section loss in plan (internal), or 10% to 50% section loss in plan (internal + external)	3
More than 75% section loss in plan (external), or More than 50% section loss in plan (internal), or More than 50% section loss in plan (internal + external)	2
Structure is threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate, 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

GENERAL DETERIORATION OF CONCRETE

________ ± ________ = ________

Initial Assessment ± Modification = Urgency Index

DESCRIPTION:

SKETCHES:

GUIDELINES	Initial Assessment
No deterioration	9
No deterioration	8
Light scaling	7
Moderate scaling or light spalling	6
Heavy scaling or moderate spalling or cracking over reinforcing steel.	5
Heavy spalling with reinforcing steel exposed	4
Severe spalling with reinforcing steel free-standing	3
Heavy section loss	2
Structure is threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate, 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

GENERAL DETERIORATION OF TIMBER

______	$\pm$	______	=	______
Initial Assessment		Modification		Urgency Index

DESCRIPTION: ____

____

____

____

____

SKETCHES:

GUIDELINES	Initial Assessment
No deterioration	9
No deterioration	8
Light weathering	7
Moderate weathering Light splintering	6
Light decay or Moderate splintering with gapping or Heavy weathering	5
Moderate decay or Heavy splintering with gapping to heartwood or Moderate biological growth	4
Heavy decay Heartwood deteriorated	3
Advanced decay or Heavy biological growth or Heavy loss of section	2
Structure is threatened	1
Structure is closed	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated, 3. Deficiency has history in similar circumstances of being self correcting, 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

SETTLEMENT

________ ± ________ = ________

Initial Assessment ± Modification = Urgency Index

DESCRIPTION: ____

SKETCHES:

GUIDELINES	Initial Assessment
No settlement	9
No settlement	8
Minor settlement or tilting of substructure	7
Moderate settlement or tilting of substructure. Joints are less than design opening.	6
Ridability impaired. Bearing devices and joints are fully open or closed before full design movement has occurred.	5
Thru cracks visible in substructure, no dislocation. Bearing devices and joints are locked.	4
Thru cracks visible with moderate relative displacement. Joints spalling from induced stress.	3
Thru cracks visible with major relative displacement. Major settlement or tilting substructure.	2
Structure is threatened.	1
Structure is closed.	0

DESCRIPTION	Modification
No threat for minimum of 5 years and one or more of the following: 1. Deficiency condition is stable; 2. External causes of deterioration substantially reduced or eliminated; 3. Deficiency has history in similar circumstances of being self correcting; 4. Deficiency is entirely "cosmetic" in nature and has little or no structural effect. (Note: May be used for original rating of 2 to 6 inclusive.)	+2
No threat for minimum of 3 years and one or more of the following: 1. Deficiency condition is worsening slowly; 2. External causes of deterioration have lessened somewhat; 3. Deficiency has history in similar circumstances of growing no worse; 4. Deficiency is mostly "cosmetic" in nature and has little structural effect. (Note: May be used for original rating of 2 to 7 inclusive.)	+1
No threat for minimum of one year and one or more of the following: 1. Deficiency condition worsening at expected or "normal" rate; 2. External causes of deterioration have remained constant; 3. Deficiency has history in similar circumstances of growing worse at consistent rate; 4. Deficiency has structural effect but has not seriously reduced structural capacity. (Note: May be used for any original rating.)	0
Threat anticipated within one year and one or more of the following: 1. Deficiency condition worsening at increasing rate; 2. External causes of deterioration are gradually increasing; 3. Deficiency has history in similar circumstances of growing worse at gradually increasing rate; 4. Deficiency has structural effect. (Note: May be used for original rating of 3 to 8 inclusive.)	-1
Threat is imminent and one or more of the following: 1. Deficiency condition is worsening rapidly; 2. External causes of deterioration are rapidly increasing; 3. Deficiency has history in similar circumstances of growing more severe at rapidly increasing rate; 4. Deficiency has severe structural effect. (Note: May be used for original rating of 4 to 8 inclusive.)	-2

THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The Transportation Research Board operates within the National Research Council. The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine.

The National Academy of Sciences was established in 1863 by Act of Congress as a private, nonprofit, self-governing membership corporation for the furtherance of science and technology, required to advise the Federal Government upon request within its fields of competence. Under its corporate charter the Academy established the National Research Council in 1916, the National Academy of Engineering in 1964, and the Institute of Medicine in 1970.

TRANSPORTATION RESEARCH BOARD

National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

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

003901Y
NATIONAL ACADEMY OF SCIENCES

LIBRARY
2101 CONSTITUTION N W
WASHINGTON DC 20418

3