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REPAIR, EVALUATION, MAINTENANCE, AND
REHABILITATION RESEARCH PROGRAM

2

US Army Corps
of Engineers

TECHNICAL REPORT REMR-OM-11

REMR MANAGEMENT SYSTEMS—COASTAL/ShORE
PROTECTION STRUCTURES: CONDITION
RATING PROCEDURES FOR RUBBLE
BREAKWATERS AND JETTIES
INITIAL REPORT

by

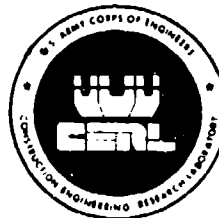
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May 1991

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CS Concrete and Steel Structures	EM Electrical and Mechanical
GT Geotechnical	EI Environmental Impacts
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PREFACE

The study reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Operations Management problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Civil Works Research Unit 32280, "Development of Uniform Evaluation Procedures/Condition Index for Deteriorated Structures and Equipment," for which Dr. Anthony M. Kao is Principal Investigator. Mr. James E. Crews (CECW-OM) is the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. Crews and Dr. Tony C. Liu (CECW-EG) serve as the REMR Overview Committee; Mr. William F. McCleese (CEWES-SC-A), US Army Engineer Waterways Experiment Station (WES), is the REMR Program Manager. Dr. Kao is the Problem Area Leader for the Operations Management problem area.

This work was conducted by the US Army Construction Engineering Research Laboratory (USACERL) under the general supervision of Dr. Paul Howdyshell, Acting Chief of the Engineering and Materials Division (EM).

The authors extend their appreciation to all those who worked on and supported the project, and especially to Dr. Kao for his guidance throughout the project and his confidence in the product.

The authors also thank the Coastal Structure Advisory Group for their ideas and their review of project material: David Campbell (CESWG-ED-F), Larry Cook (CELMV-ED-WH), Joe Gurule (CESAJ-EN-HC), John Housley (CECW-PF), Andy Lamborghini (CENED-ED-DE), Henry Nakashima (CEPOD-ED-TS), Gil Nersesian (CENAN-EN-DN), John Oliver (CENPD-EN-TE), Doug Pirie (CESPD-CO-ON), and Ed Stepek (CENCD-CO-C).

A special note of appreciation is extended to Ross Kittleman for his ideas and support throughout the project and for the suggestion of forming the Coastal Structure Advisory Group, and also to Mel Simpson for his help in the quantification of condition levels.

The authors appreciate the assistance from the Philadelphia and Buffalo Districts in conducting field tests, and from Larry Sandhaas and John Pearson (USACERL) in creating the inspection forms and assembling this report. COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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REMR MANAGEMENT SYSTEMS-COASTAL/SHORE PROTECTION
STRUCTURES: CONDITION RATING PROCEDURES FOR
RUBBLE BREAKWATERS AND JETTIES, INITIAL REPORT

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers is responsible for the maintenance of several hundred coastal and navigational structures. In an effort to help the Corps improve maintenance techniques and practices, the US Army Construction Engineering Research Laboratory (USACERL) is conducting research under the Repair, Evaluation, Maintenance and Rehabilitation (REMR) program. The philosophy is that the key to good maintenance management is a good understanding of the current condition of facilities and the ability to project future condition. This capability then permits successful maintenance planning--the process of establishing the most cost-effective allocation of a maintenance budget.

2. Beyond this basic philosophy, this research intends to create more uniform procedures for evaluating the condition of structures than are now available. It also will create methods by which the condition of structures and their parts can be expressed numerically to take best advantage of micro-computer technology in maintenance management.

Current Inspection Methods

3. Current methods of inspecting coastal structures are usually at the discretion of Districts and Divisions. These methods vary considerably throughout the Corps, and often within Divisions. Methods range from casually walking over each structure on an irregular interval (1 to 5 years) and reporting general observations (usually by trip report) to more sophisticated procedures. The latter include taking aerial photographs, sending survey crews to the site to take detailed above-water measurements, and conducting side scan sonar or diver inspections below water. In addition, observations made by individual inspectors may vary, based on their respective backgrounds and training.

4. Structures that perform well functionally and/or have a history of being stable are often assumed to require no attention until some problem becomes obvious or is reported by the general public. Other factors that may influence the inspection process are the importance of the structure, time available for inspection, accessibility of the structure, and the manpower and equipment available to acquire the data.

Project Overview

5. This report describes the development of a numerical condition rating method for breakwaters and jetties of all--or primarily--rubble construction with either rock or concrete armor. The condition rating procedure is intended to make inspections more uniform and consistent.

6. The method is based on a rating of various structural aspects of breakwaters and jetties made during a visual inspection, along with functional considerations. These ratings are then combined to produce a condition rating for the seaside, leeside, and crest of each reach, then for each reach, and finally, for the whole structure. USACERL is developing a computerized coastal structure maintenance management program that will incorporate this condition rating system.

The Coastal Structure Advisory Group

7. One difficulty in developing a uniform coastal structure condition rating method is in creating a system equally suited for the variety of structures and wave climates found along all the coasts and the Great Lakes. To provide input on these and other variables, as well as general guidance on the project, the Coastal Structure Advisory Group (CSAG) was formed.

8. This group consists of one representative from each of the nine Corps Divisions that border the Atlantic, Pacific, Gulf, and Great Lakes coasts, and one representative from the Office of the Chief of Engineers (OCE). Throughout the project, this group reviewed material, participated in field tests, and offered ideas on creating a simple, but meaningful, system.

Objective

9. The main objective of this work is to create a uniform, numerical condition rating system for coastal protection structures. This system should conform with the assessment that knowledgeable inspectors would make, based on the results of their own visual inspections. It also should be simple and definitive enough to be applied consistently by those without extensive training and experience, and further, designed for easy manipulation in a microcomputer (to serve as a basis for a coastal structure maintenance management program).

10. A longer range objective is to have the completed system serve as a universal language for describing the condition of coastal protection structures.

Approach

11. The research for this project was conducted as a joint effort between USACERL and the Coastal Engineering Research Center (CERC) at the US

Army Engineer Waterways Experiment Station. While USACERL was responsible for overall project management and creating a system consistent with REMR Operations Management objectives, CERC had responsibility for technical development and assuring a system compatible with coastal engineering principles.

12. Concepts for the condition rating system were generated by the authors, CSAG, and other members of the coastal community. These concepts were refined by the authors and sent to the CSAG for review. Further revisions and refinement came through field testing by CERC, USACERL, and the CSAG.

Scope

13. There are several types of coastal protection structures, and each may have more than one specific purpose. In addition, construction types can vary considerably among structures and even between different sections of a structure. For the early phase of this research, it was decided to concentrate on structures similar in function and construction to minimize the variables encountered. The structures chosen were breakwaters and jetties of all--or primarily--rubble construction with either rock or concrete armor. Thus, at this time, the rating system under development is intended to apply only to this group of structures.

14. Additional work and field testing will be needed to complete and refine the process. This report describes the work that has been completed to date.

PART II: THE CONDITION INDEX

Background

15. The Operations Management portion of the REMR research program is devoted to creating field procedures and computer programming that makes maintenance planning uniform, fast, and easy--a goal that suggests the use of computerized maintenance management systems. Such systems use the same concepts as the Engineered Management Systems (EMS) developed by USACERL (Shahin, Bailey, and Brotherson, 1987; Shahin and Kohn, 1981). EMS products have been created (and are under development) for a wide variety of facilities at Army installations. These systems also are based on the philosophy that the key to good maintenance management is a clear understanding of the current condition of facilities and the ability to project future condition.

16. Early in EMS development, it was noted that facility condition assessment is typically a highly individualistic process, varying considerably with each inspector (as is often the case for inspection of coastal protection structures). This situation made it difficult to compare inspections between like facilities or for the same facility over time. To improve the uniformity of the inspection and condition evaluation process, and to take better advantage of microcomputer capabilities, the concept of a "condition index" was formed.

17. A condition index provides a way to express the condition of a facility numerically. A scale of 0 to 100 was chosen, with 0 worst and 100 best. Along with this scale, uniform inspection procedures were developed, as were standard procedures for arriving at the condition index values. With this system, the condition of structures and their parts can be expressed uniformly on a calibrated scale, similar to the idea of the temperature scale or the measurement of sound level in decibels.

18. It was intended that condition index ratings be producible from visual observations and simple measurements. The procedures for determining the index number must also result in consistent ratings, independent of the individual inspector who is applying the rating procedures.

19. As with USACERL's EMS products, the core of all navigational and coastal structure maintenance management systems is the condition index (Yu and Kao, 1989; Bullock, 1989; Greimann, Stecker, and Rens, 1989; Greimann and Stecker, 1989). The standard REMR condition index scale is described below and shown in Table 1. This scale is the one used for rating the condition of coastal structures.

Table 1
REMR Condition Index Scale

Observed Damage	Zone	Condition Index	Condition Description	Recommended Action
100 Minor 70	1	95 to 100	EXCELLENT - No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
		70 to 84	VERY GOOD - Only minor deterioration or defects are evident.	
60 Moderate 40	2	55 to 69	GOOD - Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
		40 to 54	FAIR - Moderate deterioration. Function is still adequate.	
30 Major 0	3	25 to 39	POOR - Serious deterioration in at least some portions of structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
		10 to 24	VERY POOR - Extensive deterioration. Barely functional.	
		0 to 9	FAILED - No longer functions. General failure or complete failure of a major component.	

The REMR Condition Index

Definition

20. The REMR Condition Index (CI) is a numbered scale, from 0 to 100. The numbers indicate the relative need to perform REMR work due to general deterioration of the structure or functional and safety considerations.

Intended Application

21. The condition index is primarily a planning tool, with the index values serving as a rough indicator of the structure's general condition level. The index is meant to act as a guide in focusing management attention on those structures most likely to warrant immediate repair or further evaluation. In addition, the CI values can be used to monitor general condition change over time and can serve as a rough comparison between the conditions of different structures.

Determination of Condition Index Numbers

22. CI numbers can be determined from any measurable or observable characteristic or attribute that can be related to the physical condition, function, or safety of the structure. For a given structure type, the procedures for producing the condition index number must be standard, objective, and repeatable. Further, these procedures must be simple enough to be applied successfully by those without a high level of training and experience.

General Interpretation of the REMR Condition Index Scale

23. The CI scale is calibrated to group structures into three basic action categories (or zones). Those structures (or portions thereof) in good condition and requiring no more than routine maintenance or minor repair are grouped into Zone 1 (70 to 100). In the middle is Zone 2 (40 to 69). This zone includes structures and major structural parts that show signs of deterioration, but still maintain at least some acceptable function. At the bottom, Zone 3 (0 to 39) includes structures and major parts in need of immediate attention to restore proper function and/or structural integrity.

24. As the transition area between clearly good and clearly poor, Zone 2 is perhaps the most active zone. It is within this zone that most economic evaluations, prioritizations, and maintenance decisions commonly occur.

25. It is essential to note that the condition index ratings are intended to be indicators--not absolutes. They are based on visual inspections, not on detailed investigations, and should be interpreted and used as such.

Producing a Condition Index Rating

26. While later sections will describe the detailed process of producing the condition index rating, an overview of the process is in order here. Generally, the condition index rating is produced through a "pyramid" process. This process begins by rating various aspects of each structural reach. These ratings then are combined to produce ratings for a major part of the structural section. Similarly, the ratings for the major parts are combined into a rating for each structural section, and these, in turn, are combined to result in a rating for the structure as a whole. Figure 1 represents this process for the Structural Index.

27. Thus, several ratings are combined (using a standard set of rules) in several stages to finally produce a single number representing the overall rating for a complete structure. The condition rating numbers can be examined and used at any or all levels, depending on the degree of detail required at the time.

28. For coastal structures, structural integrity and structural performance do not always coincide, as in 1987 at Lake Michigan when several structures in good physical condition failed functionally; the record high water levels left them too low to provide their usual degree of wave protection. For this reason it was decided that structural and functional aspects should be evaluated separately, with these evaluations joined near the final determination of the condition index rating.

29. Parts III and IV cover the structural and functional ratings, respectively. An explanation of how they are combined into a final condition rating is presented in Part V.

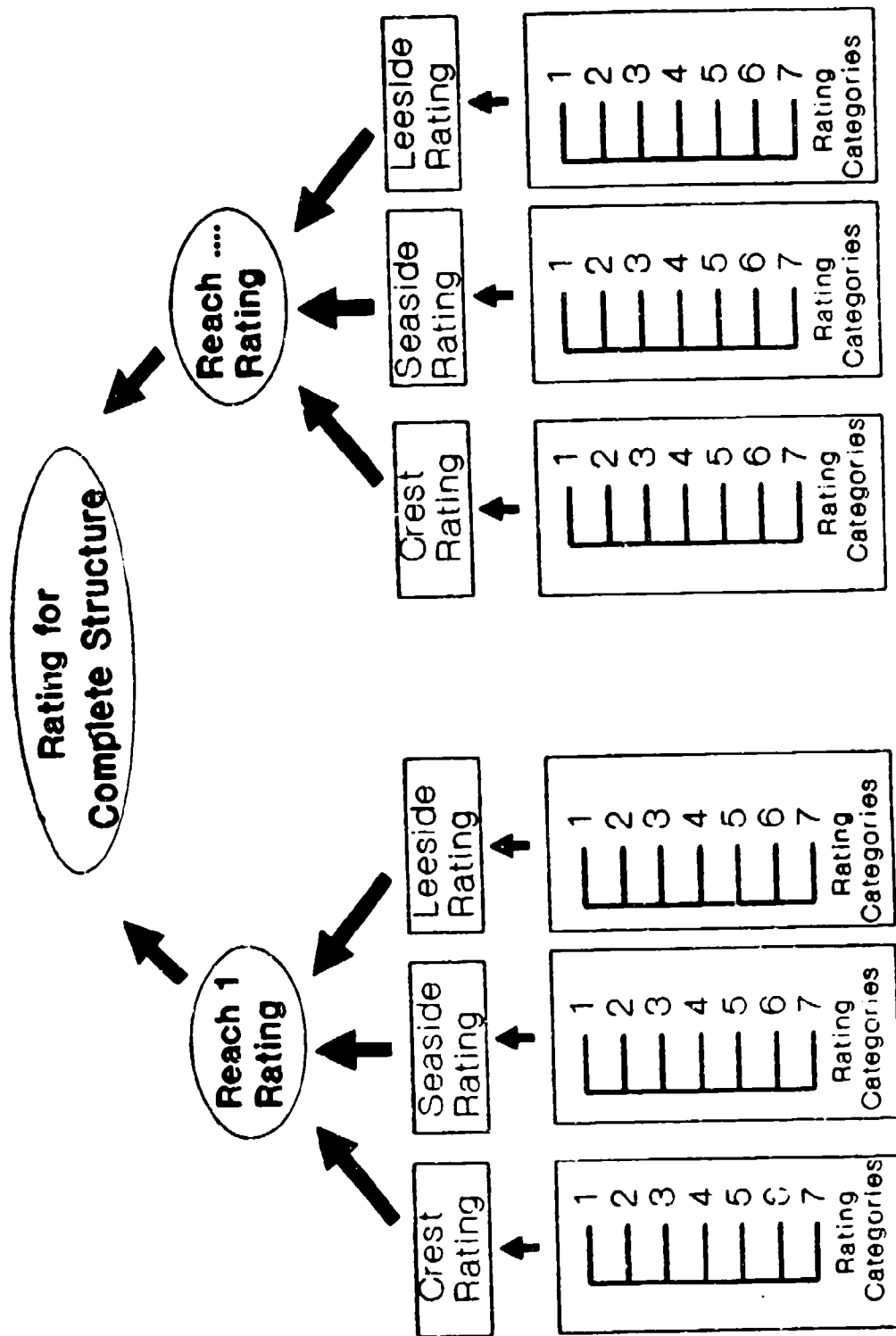


Figure 1. Structural index pyramid

PART III: STRUCTURAL RATING

Introduction

30. The intended end product of the structural rating procedure is a structural index (SI) number that correlates to the existing physical condition of the structure.

31. The current rating process evolved in three phases, each accomplished through working with the CSAG. All phases involved the following basic steps:

- a. Determine which physical aspects of a structure should be evaluated.
- b. Divide the structure into component parts to accommodate the rating process.
- c. Develop the method for producing the structural index number.

32. Each phase of development resulted in its own field inspection form. Completed examples for Phases 1 and 2 appear in Figures 2 and 3, and a blank copy for Phase 3 is shown in Figure 4. These figures will be used to illustrate the method produced for each phase. The terms for Phase 3 are defined in Tables 2 and 3 in the next section.

33. The Phase 1 form and procedure were field-tested by WES, USACERL, and the Philadelphia District at several structures on the New Jersey and Delaware coasts: Manasquan Inlet, NJ; Absecon, NJ; Cold Spring Jetty at Cape May, NJ; Delaware Bay Breakwater at Lewes, DE; and Indian River Jetty at Indian Beach, DE. The Phase 2 form and procedure resulted from these field tests. This phase was, in turn, reviewed by the CSAG and field-tested by WES, USACERL, and the CSAG at structures in the Cleveland area: Edgewater Breakwater, Cleveland East Breakwater (on sections with dolos armor, laid-up stone, and random stone construction), and Geneva Easc Jetty. These field tests, along with a CSAG meeting, led to development of the Phase 3 inspection.

General Design of the Inspection Forms

34. Two objectives in designing the structural rating system were to keep it simple and concise. These objectives applied to the design of the field inspection forms as well. For conciseness, it was desirable to design the forms so that a single page (one side) could handle all information required for the inspection of one reach, including basic information identifying the structure, the inspector's name, weather and wave conditions, supplementary information, and comments and sketches. For simplicity, the forms were designed to require a minimum amount of writing; most inspection information is supplied by marking the appropriate item or by writing a number or letter.

INSPECTION/EVALUATION FORM FOR DETERMINING CONDITION INDEX FOR RUBBLE-MOUND COASTAL STRUCTURES

PROJECT Bay City Breakwater

DATE 14 Jun 88

INSPECTOR J.P. Davidson

PAGE NO. 1

- I. PROJECT Bay City Breakwater
 II. DISTRICT Atlantic
 III. LOCATION State
 IV. TYPE OF STRUCTURE Breakwater
 V. TYPE OF INSPECTION Visual
 VI. STATE OF INSPECTION Visual
 VII. FIELD EVALUATION:

FIELD RATING STRUCTURAL COMPONENTS	Type Material: <u>Concrete</u> Observed Damage: <u>Major, Moderate, Minor</u> Sealant/Leakage	Sta. <u>0</u> to Sta. <u>200</u> Concrete Area: <u>10.136</u> Steel: <u>12.113</u>	Erosion Control: <u>None</u> Average Rating: <u>67</u>	Comments: <u>Sealant, etc.</u>
1. BREACHING OF SECTION A. Dislocated armor B. Settling of armor C. Other	<u>mi, 1 mi</u>	<u>90, 90</u>	<u>18, 18</u>	<u>Reach 1 2 3 4</u> <u>me 0 started at steel gate.</u>
2. ARMOR DISPLACEMENT A. Oriented imbedded B. Out of Position C. Other	<u>mi, 1 mi</u>	<u>80, 90</u>	<u>13, 14</u>	
3. EXPOSURE OF UNDERLAYER/CORE MATERIAL A. Leaching B. Direct Exposure C. Other	<u>mi, 1 mi</u>	<u>90, 95</u>	<u>12, 13</u>	
4. CONDITION OF CAP A. General deterioration B. Breaching (settling, spalling, etc.) C. Displacement D. Settling	<u>mi, 1 mi</u>	<u>90, 90</u>	<u>12, 12</u>	
5. DRAINAGE IN SIDE SLOPES A. Slumping B. Flattening (vertical) C. Slumping D. Other	<u>mi, 1 mi</u>	<u>95, 95</u>	<u>12, 12</u>	
6. ARMOR CORROSION A. Pitting B. Spalling C. Rusting D. Other	<u>mi, 1 mi</u>	<u>90, 90</u>	<u>11, 11</u>	
7. BELOW WATER INDICATORS A. None B. Armor Displacement C. Armor Slumping D. Slope Slumping	<u>mi, 1 mi</u>	<u>95, 95</u>	<u>11, 11</u>	
Cf Rating Per Reach				Avg. Rating <u>69</u>

12. DAMAGE TO AUXILIARY STRUCTURES (walkways, stairs, navigation lights, etc.)
 A. Major B. Moderate C. Minor D. None

13. AMOUNT OF DAMAGE IN ARMOR (rubble, trash, logs, etc.)
 A. Major B. Moderate C. Minor D. None

* Reaches must be of equal length to obtain overall avg. rating.
 ** See "Definition Index" for Submerged Coastal Structures

Figure 2. Phase 1 structural inspection form.

INSPECTION/EVALUATION FORM FOR DETERMINING STRUCTURAL CONDITION INDEX FOR RUBBLE-MOUND COASTAL STRUCTURES

PROJECT/STRUCTURE: BAY CITY Beach Nourishment DATE: 9 Sept 88 Sta. 0 to Sta. 2500, REACH 1.0

DISTRICT: 1st District INSPECTOR: Bob Davidson

LOCATION: Bay City, Michigan MAP: 1000 (Scale 1" = 100')

TYPE OF STRUCTURE: Beach Nourishment (Circle appropriate item)
 A. Breakwater B. Bulkhead C. Dike D. Embankment E. Groin F. Jetty G. Pier H. Quay I. Revetment J. Seawall K. Shoreline Protection L. Tidal Wall M. Other

TYPE OF INSPECTION: Visual (Circle appropriate item)
 A. Visual B. Underwater C. Dredge D. Other

WEATHER DAY OF INSPECTION: Clear (Circle appropriate item)
 A. Fair B. B. C. Fog D. Storming

SEA CONDITION DAY OF INSPECTION: Calm (Circle appropriate item)
 A. Calm B. Medium (3-5') C. High (5-7') D. Very High (7-10') E. Other

FIELD EVALUATION

STRUCTURAL COMPONENTS	OVERALL DAMAGE: A. None C. Moderate B. Minor D. Major	CI Rating (CI Scale) 0-100 Factor Rating	WEIGHTING Factor Rating	Comments, Sketches, etc.	
1. BREACH/LOSS OF SECTION (Length x Width x Depth) A. Displaced Armor B. Settling of Armor C. Other	B	90	20.30	27	Armor 3 ft x 3 ft x 3 ft 3 ft x 3 ft x 3 ft 3 ft x 3 ft x 3 ft
2. DAMAGE TO CIP/CAST A. Type Material B. General deterioration (Cracking, spalling, etc.) C. Displacement D. Exposure of Underlayer	B	90	20.20	18	
3. SIDE SLOPE/BEACH (1) SEASIDE (Type Armor, E. Settling) A. Slumping C. Settling B. Slumping D. Exposed Underlayer (2) LICESIDE (Type Armor, E. Settling) A. B. C. D. E. F. G. H. I. J. K. L. M. N. O. P. Q. R. S. T. U. V. W. X. Y. Z. (3) BEACH (Type Armor, E. Settling) A. B. C. D. E. F. G. H. I. J. K. L. M. N. O. P. Q. R. S. T. U. V. W. X. Y. Z.	B	95	20.13	12	
4. ARMOR DAMAGE A. Type Armor B. Pitting C. Spalling D. Rounding E. Cracking F. Breasting G. Other	B	90	20.13	12	
5. BELOW WATER INDICATION A. None B. Armor Displacement C. Armor Slumping D. Slope Slumping E. Slope Flattening F. Other	B	95	20.11	10	
CI Rating for beach		90		91	

OVERALL STRUCTURE RATING
 Lowest CI Rating 90
 Avg. Avg. CI Rating 91

Comments, Sketches, etc.

Sketch of beach profile showing armor placement and beach width.

Figure 3. Phase 2 structural inspection form.

INSPECTION FORM FOR DETERMINING STRUCTURAL INDEX (S.I.) FOR RUBBLE-MOUND COASTAL STRUCTURES Reach _____ Page ____ of ____

PROJECT/STRUCTURE: _____ Time: _____ Inspection Date: _____

LOCATION: City _____ State _____ Harbor, Bay, Lake, etc. _____

DISTRICT: _____ INSPECTOR: _____ Reach Length _____

SEA CONDITION A. Calm (<3') TIDE LEVEL: _____ WEATHER DAY OF INSPECTION: Sta _____ to Sta _____
 DAY OF INSPECTION: B. Medium (3'-5') A. High C. Falling A. Fair B. Rain
 C. High (>5') B. Rising D. Low C. Fog D. Storming

TYPE OF INSPECTION: A. Walking B. Boating C. Other _____

TYPE OF STRUCTURE: (Circle one from each pair) A. Breakwater C. Shore Connected E. Overtopping
 B. Jetty G. Offshore F. Non-overtopping

TYPE OF ARMOR: Crest/Cap _____ Seaside or Head _____ Leeward _____

RATING CATEGORIES	CREST / CAP			SEASIDE (or HEAD)			LEESIDE		
	Obs'd Damage Level	Station ____ to ____	Rating 0-100	Obs'd Damage Level	Station ____ to ____	Rating 0-100	Obs'd Damage Level	Station ____ to ____	Rating 0-100
Breach: A) Displaced Cap/Armor B) Settling Cap/Armor				////	////////	////	////	////////	////
Armor Loss: A) Displaced B) Settling C) Bridging									
Armor Qual. Defects: A) Pitting B) Cracking C) Breaking									
Lack of armor contact / armor interlock									
Core Exposure / Loss									
Slope Defects: A) Steepening B) Settling C) Slumping	////	////////	////						
	CREST/CAP RATING			SEASIDE RATING			LEESIDE RATING		

S.I. RATING FOR REACH _____

BELOW WATER INDICATIONS: A. Armor displacement B. Armor slumping C. Slope steepening D. Slope flattening E. None Visible

AMOUNT OF DEBRIS IN ARMOR (rubble, trash, logs, etc.): 0. None 1. Minor 2. Moderate 3. Major

DAMAGE TO AUXILIARY STRUCTURES (walkways, stair, navigation lights, etc.): 0. None 1. Minor 2. Moderate 3. Major

COMMENTS AND SKETCHES

Rev 12/28/90

Figure 4. Phase 3 structural inspection form.

Table 2

Component Definitions for Phase 3 Structural Rating

Crest (or cap) - the uppermost part of a structure's cross section, usually above water; may provide added wave protection, an overtopping barrier, or access to the structure for repair and inspection.

Head - the outermost end(s) or terminal section(s) of a structure; often radial in shape, and extending to the point where the structure becomes uniform in cross section.

Leeside slope - the face of the structure opposite from the primary direction of wave attack; e.g., harbor side, channel side, marina side.

Reach - length of structure whose limits can be determined by physical changes such as armor type, construction, or cross section design, or set arbitrarily as a means for dividing the structure into convenient-sized sections. The head of a structure is often treated as a separate reach.

Rubble-mound structure - mound of random-shaped and -placed stones protected with a cover layer of selected stones or specially shaped concrete armor units. (Armor units in primary cover layer may be placed in orderly manner or dumped at random.)

Seaside slope - slope of the structure exposed to the open sea or water body. Side that is attacked most by naturally occurring waves, e.g., oceanside, bayside, lakeside.

Table 3
Rating Category Definitions for Phase 3 Structural Rating

Armor contact (rock armor) - the tightness of the armor stones in-place; how close or compact the individual armor stones are fitted together. Good armor contact results in maximum surface contact between individual armor stones.

Armor interlock (concrete armor units) - the degree to which armor units are nested or interlocked. With good armor interlock, individual units cannot rock in place or slide out of their placed position.

Armor loss - the amount of armor missing and the extent to which it has been displaced; i.e., how much armor has been lost; is it still in place but has settled significantly; has the armor been displaced out of position but remains on the structure or is it lost from sight; are there large voids bridged by the armor material?

Armor quality - the condition of the individual armor stones or units; i.e., is stone armor cracked, split, or rounded; are concrete armor units pitted, spalled, rounded, cracked, or broken?

Breach - a location with reduced cross section elevation due to displacement of armor across the width of the crest or cap, or settling of the crest, significant enough to potentially affect the structural integrity and/or function.

Core exposure/loss - the extent to which core and/or underlay materials are exposed or lost. (Signs of leaching and/or exposure of the underlayer materials are indicators of serious instability or potential future problems.)

35. In addition, when a whole structure is inspected during a single visit (as is usually the case), complete identification information is required only for the first page. Information at the top of subsequent pages is needed only to keep track of the reaches and for cases in which information changes from reach to reach.

36. For all phases, the inspection forms are organized with identifying information at the top, primary inspection in the center, and supplementary information at the bottom. The design and vertical format for Phase 3 provide the additional advantage of allowing the form to be stored easily in a computer and printed using most IBM-compatible microcomputers and printers (Figure 4).

37. Common to all of these structural inspection forms are the line items at the bottom for "Amount of Debris in Armor" and "Damage to Auxiliary Structures." These items are not intended to directly affect the structural rating, but are included because debris on the structure and damage to auxiliary structures may require action by the District, and are thus important to note.

Definitions

38. An essential part of developing a uniform inspection procedure is to establish standard definitions and descriptions for all criteria, categories, components, and terms used in the system. Tables 2 and 3 list the component and rating category definitions, as developed to date, for Phase 3 structural rating.

Dividing a Structure Into Component Parts

39. The first and easiest of the decisions in this area was the longitudinal division of the structure into reaches. From the beginning, it seemed natural that each reach of a structure should receive its own rating. Not settled was the question of whether the reaches should be equal in length or correspond to natural divisions in the structure (such as changes in armor type) or current reach definitions used by individual Corps Districts. Each choice appeared to have clear advantages and disadvantages.

40. Due to the procedure chosen for Phases 1 and 2, reaches needed to be equal in length. This was not the case for Phase 3, which was designed to work about equally well regardless of reach length. Thus, Districts can use their current reach definitions with this method. While reach lengths within a structure may be quite different, it is important to note that once defined, reach limits should not be changed from one inspection period to another, as this would make condition comparisons over time much more difficult.

41. As with the longitudinal divisions (reaches), the cross sectional divisions also changed from Phase 1 to Phase 3. With Phase 1 (see Figure 2, third column), the visible seaside and leeside of each reach were rated separately. While the seaside and leeside slopes appear as separate items within the rating categories for Phase 2 (Figure 3), the whole visible cross section is treated essentially as one component. This was done in an attempt to simplify the system and to reduce the volume of numbers to be handled. This procedure proved to be an oversimplification, however, as the wave effects vary over the cross section and the different areas apparently need separate examinations to ensure that enough information is provided from the inspection. Phase 3 (Figure 4) divides the cross section into three distinct components: the crest (or cap) and seaside and leeside slopes. If the head of the structure is rated as a separate reach, all slope faces are treated as the seaside slope.

The Rating Categories

42. As a group, these rating (or defect) categories are intended to answer the question "What primary types of defects should be anticipated when making a visual structural inspection." Table 4 lists the rating categories used in each phase, and Figures 2 through 4 show how they were applied for each inspection.

43. While the rating categories vary for each phase, the three inspection versions are, in fact, not as divergent as they might first appear. The different rating categories used for each phase are primarily due to the way in which the structure's cross section has been divided. Thus, the differences between inspection forms do not reflect radically different types of inspections for each phase, but mainly a different method of treating the defect types and cross sectional components.

44. The basic difference between Phases 1 and 2 is that the Phase 1 inspection provides separate ratings for the seaside and leeside of the structure, whereas the Phase 2 inspection leads directly to a single rating for the whole reach cross section. The Phase 3 inspection supplies the most detail by providing separate ratings for the crest (cap), seaside, and leeside. It is also somewhat more thorough, with an added rating category--Lack of Armor Contact/Armor Interlock.

45. While Phase 3 contains two rating categories not found in Phases 1 and 2, it also appears to lose one: Below Water Indicators. The consensus was that such indicators are not always present or easy to see for someone with limited experience, and therefore, it would be difficult to treat this category consistently in determining a structural rating. However, visible Below Water Indicators are considered to be so important that it was decided

Table 4
Rating Categories for the Three Phases

<u>Phase I</u> (Separate Seaside and Leaside Rating)	<u>Phase 2</u> (Rating for Whole Structure)	<u>Phase 3</u> (Separate Ratings for Crest, Seaside, and Leaside)
1. Breaching of Section	1. Breach/Loss of X-Section	1. Breach
2. Change in Side Slopes	2. Side Slope/Head (Seaside, Leaside)	2. Slope Defects
3. Armor Condition	3. Armor Damage	3. Armor Quality Defects
4. Condition of Cap	4. Damage to Cap/ Crest	4. Armor Loss
5. Below Water Indicators	5. Below Water Indicators	5. Lack of Armor Contact/Interlock
6. Exposure of Under- layer/Core Material		6. Core Exposure/Loss
7. Armor Displacement		

to keep this category as a separate item (near the bottom of the form) rather than eliminate it entirely. How this item will be handled in the reach rating has yet to be determined.

46. In addition to noting primary defects, it was thought useful to provide some indication of how the defect appeared, or in what form it was observed. This information is obtained through short lists included within the rating categories which can be marked to provide more detail from the inspection. These listed items are intended for additional information only; they do not directly affect the numerical rating, but may aid in determining the appropriate category rating.

Determining the Structural Rating

Phases 1 and 2

47. Both phases have a similar procedure for determining the SI for a reach. As shown in Figures 2 and 3, the relative level of defects is first indicated in the second column, "Observed Damage." The choices available are none, minor, moderate, or major, which are intended to correspond with the three zones in the CI scale (Table 1). Once the defect levels have been

chosen, the numerical rating is then selected; it must fall within the zone corresponding to the damage level chosen. The numerical ratings are then multiplied by the weight factors printed to the right, and the resulting numbers are added together to arrive at the reach SI.

48. The weight factors were determined from a consensus of the CSAG. They were asked to rank the relative importance of the rating categories and to note their own weight factor preferences. These weight factors were then normalized so that an SI number would always be produced in the range from 0 to 100.

Status of Phase 3

49. As with Phases 1 and 2, the Phase 3 form has columns for "Observed Damage Level" (see Figure 4) which can permit some checking of the correctness and consistency of the numerical rating recorded for each category. These levels are noted by recording a number from 0 (none) to 3 (major) that corresponds to the zone number on the condition index scale.

50. The "Station" columns allow inspectors to record both the location of a defect and its extent (length) by using standard surveyor's stationing. The stationing is intended to match that shown on project drawings and/or marked on the structure.

51. The rules for selecting the numerical rating for each rating category and for establishing the reach SI rating are not yet completed. When done, Phase 3 will provide for these numerical ratings, along with ratings for the crest, seaside, and leeside of the structure as well as a single SI rating for the reach.

52. The weightings assigned to the categories and the rules for their ultimate combination into a single rating for the reach will not likely appear on the form. These weightings and rules will be contained in the computerized maintenance management program for which this rating system is being developed. The inspection form will serve as one method for recording the inspection information, which will then be entered into the coastal maintenance management computer data base. The management program will make all calculations and print several types of reports showing the inspection and rating results.

Structural Rating for a Complete Structure

Introduction

53. Once the general procedures for determining the SI of each reach were developed, a method was needed for combining the reach ratings into a single rating that represents the overall structural condition for the complete structure. This process began by tapping the thought processes and reasoning that members of the CSAG use in their own evaluation of structures. Then guidelines were established based on input from the CSAG and concepts

established for the REMR program as a whole. Finally, a mathematical formula was developed that closely matched the behavior dictated by the guidelines. The rest of Part III describes this development process in more detail. The concepts are described along with the guidelines formed from them. Then the method by which the mathematical formula was created to follow the guidelines is discussed.

General Concepts and Guidelines

54. The following concepts and guidelines relate to establishing upper and lower bounds on the SI number. The basic mathematical expression that follows from them is included. The list begins with the most general ideas and then begins to narrow the scope of the guidelines for creating the SI formula.

- a. Concept 1. As established for the whole REMR management system, all condition rating indexes are built on a scale from 0 to 100, with 100 being the best and 0 the worst.
- b. Guideline 1. The SI number must stay in the 0 to 100 range.
- c. Concept 2. The structure, as a whole, cannot be better than the highest rated reach nor worse than the lowest rated reach.
- d. Guideline 2. The SI number must be somewhere between the lowest rated reach and the highest rated reach.
- e. Concept 3. A maintenance manager is most concerned about the worst portions of the structure.
- f. Guideline 3. The lowest rated reach must have the greatest impact on the SI number.
- g. Concept 4. Referring to the REMR Condition Index Scale, if a structure has a reach rated within zone 3, the SI number for the structure, as a whole, should not be above the upper limit of zone 2.
- h. Guideline 4. The SI number should never be higher than approximately 30 points above the lowest rated reach.

55. These concepts and guidelines led to the basic form of the SI as a number from 0 to 100 such that:

$$SI = L + (0 \text{ to } 30)$$

where: SI = Structure Index number

L = rating of lowest rated structure.

Establishing the Final Rating

56. The concepts and guidelines below establish the rules for determining the procedure by which up to 30 points are added to the lowest rated reach to obtain the SI for the whole structure:

- a. Concept 5. The physical condition of a structure can fall, conceptually, anywhere on the REMR Condition Index Scale.

- b. Guideline 5. The SI formula should be a continuous function, with no abrupt changes or "steps."
- c. Concept 6. While serious deterioration of a structure is most critical to note, it is also important to see small changes in condition, as they define the rate at which a structure is deteriorating.
- d. Guideline 6. Any change in the condition (or rating) of a reach should always have some effect on the SI number.
- e. Concept 7. When the condition of all reaches is the same, the condition of each reach is the same as that for the whole structure.
- f. Guideline 7. When all reaches have the same rating, the SI number should equal that rating.
- g. Concept 8. Since structures often have "natural" divisions due to changes in construction, extensions added, etc., it is desirable to keep reach divisions consistent with these "natural" or other previously established divisions. This means that reaches in a structure might have considerably different lengths.
- h. Guideline 8. Reach lengths should not have to be all the same; their differing lengths should be accounted for in the SI formula.

57. The requirements of this group of concepts and guidelines led to finalizing the SI formula as follows:

$$SI = L + \frac{(H-L)}{100} \times 30 \left[\frac{\%1}{100} \times \frac{R1}{100} + \frac{\%2}{100} \times \frac{R2}{100} + \frac{\%3}{100} \times \frac{R3}{100} + \dots \right] 100$$

Where: SI = Structural Index number
 L = rating of lowest rated reach
 H = rating of highest rated reach

%1, %2, %3... = percentage of the structure occupied by reaches 1, 2, 3, etc.
 R1, R2, R3... = structural rating for reaches 1, 2, 3, etc.

How and Why the SI Formula Works

58. The guidelines in the previous section were used to create factors that, when added to the basic expression, result in an SI formula that satisfies all the listed guidelines. The basic expression $SI = L + (0 \text{ to } 30)$ satisfies guidelines 3 and 4. Below is an explanation of how and why the other factors work.

59. At the one extreme, H can be a maximum of 100 and L a minimum of 0; thus, $(H-L)/100 = (100-0)/100 = 1$. At the other extreme, $H = L$, so, for example, $(H-L)/100$ might be $(40-40)/100$ which is 0. Thus, the $(H-L)/100$

factor always gives a number between 0 and 1, and when $H = L$, the formula results in $SI = L + 0 \times 30$, or $SI = L$, which satisfies guideline 7. This factor, combined with the expression in brackets (with the $\%/100$ and $R/100$ factors), helps satisfy other guidelines as well.

60. As with the $(H-L)/100$ factor, the expression in brackets ranges from 0 to 1. This occurs because first, the $\%$ and R variables both range from 0 to 100; thus the $\%/100$ and $R/100$ factors always range from 0 to 1. Second, $\%/100 \times R/100$ always ranges from 0 to 1. The sum of any number of $\%/100 \times R/100$ factors added together will be at most 1 because the total percentage of a structure will always equal 100. Thus, these two factors control the formula so that at least 0, and at most 30, points are added to L , which satisfies guideline 4.

61. Use of the arrangement $(H-L)/100$, along with the limits of 0 to 1 for the bracketed factor, keep the SI number in the range 0 to 100, and further, always somewhere between H and L , satisfying guidelines 1 and 2.

62. Use of the $\% \times R$ arrangement allows the length of each reach to be proportional, and also allows for reaches to differ in length, satisfying guideline 8. This arrangement also satisfies guideline 6, in that change in the rating of any reach results in some change in the SI .

63. Finally, the general construction of the formula satisfies guideline 5, producing SI numbers that cover a continuous range from 0 to 100. Now the formula can be somewhat simplified by combining a few terms to yield:

$$SI = L + 0.3(H-L) \left[\frac{\%1}{100} \times \frac{R1}{100} + \frac{\%2}{100} \times \frac{R2}{100} + \frac{\%3}{100} \times \frac{R3}{100} + \dots \right]$$

Examples

64. Figure 5 shows examples of using the SI formula described above.

The Inspection Process

65. While it is intended that the structural inspection process presented above be simple enough to be used by those without extensive knowledge and experience, it is also the intention that an inspector have enough knowledge and experience (as well as training in the use of this system) to have the confidence of the District in his/her ability to perform a competent inspection.

66. It is also intended that an inspector be aware of the following information before inspecting a structure:

- a. As-built (or modified) cross section and elevation.
- b. Previous inspections and diver surveys.
- c. Hydrographic data for the area surrounding the structure.
- d. Recent damage and repair history.
- e. Geotechnical reports.

Example 1.

Reach #	1	2	3	4	5	
Reach S.I.	30	40	50	60	70	
Reach Length	950	700	400	550	800	
% of Total Length	28%	21%	12%	16%	24%	
Total Length = 3400 ft						
						Structure S.I. = 36

Example 2.

Reach #	1	2	3	4	5	
Reach S.I.	30	95	95	95	95	
Reach Length	950	700	400	550	800	
% of Total Length	28%	21%	12%	16%	24%	
Total Length = 3400 ft						
						Structure S.I. = 45

Example 3.

Reach #	1	2	3	4	5	6	7	8	9	10	
Reach S.I.	40	45	30	35	33	32	41	42	43	44	
Reach Length	950	700	400	550	800	850	900	750	850	875	
% of Total Length	13%	10%	8%	8%	11%	12%	12%	10%	9%	9%	
Total Length = 7225 ft											
											Structure S.I. = 32

Example 4.

Reach #	1	2	3	4	5	6	7	8	9	10	
Reach S.I.	90	95	37	36	33	30	82	71	69	53	
Reach Length	950	700	400	550	800	850	900	750	850	875	
% of Total Length	13%	10%	8%	8%	11%	12%	12%	10%	9%	9%	
Total Length = 7225 ft											
											Structure S.I. = 42

Figure 5. Examples of using the SI formula

PART IV: FUNCTIONAL RATING

Introduction

67. The significance of any physical damage to, or deterioration of, a coastal structure can be determined properly only through a procedure that considers the impact of that damage on the structure's intended function(s). Thus, in addition to a structural rating, a functional rating must be developed. This task is complex, as structural function is difficult to quantify and is often associated with intangible qualities such as safety.

68. After creating an initial version of the structural rating procedure, a preliminary, or first-order, functional rating approach was discussed with the CSAG and revised to the level described in this section. This procedure has not yet been tested rigorously and will undoubtedly be revised as the full range of rubble-mound structures is explored.

69. It is anticipated that the functional rating will be assigned in the District office by an engineer or scientist who will use the results of the field inspection (the SI rating and accompanying narrative) with the project authorizing document and engineering interpretation. Knowledge of the structure's condition, the structural design intent, and coastal engineering principles will be required to determine the functional rating.

The General Process

70. The functional rating process will incorporate procedures for identifying the project purpose and function, determining relationships between structural damage and intended function, assigning values to loss of function, and finally, carrying the functional rating into an overall CI. The four basic components of the functional rating procedure are defined below:

- a. Project Purpose--both primary and secondary project purposes, (i.e., identification of the project authority and benefits intended to be provided by the project when it is in an undamaged condition).
- b. Functional Effect--the way in which functional performance has been reduced; the type of functional damage.
- c. Impact Level--the quantification of reduction in functional performance; the degree of functional damage.
- d. Function/Impact Matrix--a method of relating Functional Effect and Impact Level to produce the functional rating.

71. At this point, it is important to clarify the term "damage." As it is used in this functional rating process, "damage" refers to any characteristic of the structure that compromises its ability to perform the intended

function. Included in this definition are characteristics that might have evolved from design or construction deficiencies, changes in site conditions, or postconstruction changes to the structure.

The Four Basic Components

Project Purpose

72. Coastal navigation structures are typically jetties designed to channelize a flow and protect the entrance or breakwaters designed to surround and protect a mooring or harbor area. The scope of a structure depends on the hydrodynamic climate to which it is exposed (waves, currents, ice, water levels, sediment) and the primary structural purpose.

73. Projects also commonly have one or more secondary purposes. These are benefits derived by the presence of the structure but not originally justified for construction. Such purposes are not usually important enough to justify project construction or repair unless significant benefits can be proven.

74. Table 5 lists primary and secondary project purposes. It is important to recognize that the purposes listed in this table relate to issues determined as part of the project's authorizing documents and that the significance of these purposes is the subject of national policy.

Table 5

Primary and Secondary Project Purposes

Primary Purpose	Secondary Purpose
<u>(Project Authorization)</u>	<u>(Supplementary Benefits)</u>
- Small boat--recreational	- Protection of land and facilities
- Small boat--commercial	- Public safety
- Small boat--refuge	- Navigation aid
- Deep draft--commercial shipping	- Public access: recreation
- National defense--military	- Fishing
	- Commercial benefits

Functional Effect

75. Several aspects of a project's intended function can be compromised through structural damage, site conditions, or deficiencies in the original design. For rubble-mound harbor structures, these aspects include impact on entrance channel and harbor hydrodynamics (e.g., waves, currents, water levels) and on sediment distribution patterns in the harbor, offshore, and on adjacent beaches.

76. Generally, the types of structural damage that can compromise the project function are those which reduce structure dimensions (height, length, width) or change structure permeability. For example, loss of structure crest elevation, increased permeability, or breaching can increase wave energy inside the harbor; increased structure permeability to sediment can increase dredging costs and damage to adjacent beaches.

77. Normally, defects such as breakage of the armor cover or side slope settling would not directly affect the project's function. However, in large degrees, broken armor can create a debris problem or cause increased wave run-up and overtopping due to lower surface roughness. Thus, there are many interactive scenarios between structural defects and deficiencies and the associated functional effects.

78. After the structural inspection is completed, the results must be examined by an engineer knowledgeable about the project's purpose and the performance intent of the various structural elements. Each reach of the structure that has experienced damage, or could readily degrade further, will be reviewed to determine if that damage is great enough to result in any of the functional effects listed in Table 6.

79. The functional effects in Table 6 are divided into three groups, according to their relative importance. Those in Group 1 are considered to have a significant impact on the primary purpose of the project; any damage that could promote rapid and extensive degrading of the structure belongs in this group. Functional effects in Group 2 generally have an indirect impact on a project's primary purpose, while those in Group 3 mainly impact secondary purposes. Under the functional effects are listed some of the specific problems that might occur. These might also be envisioned as physical signs of the functional effect.

80. In some cases, it may be appropriate to conduct a future damage risk assessment to determine if the current damage is likely to promote major future damage and lead to a rapid loss of function. If so, the functional effect may be considered as already existing. Damage that results in severe functional effects, regardless of the group, could require repair, depending on the particular project purpose and level of impact.

Impact Level

81. Table 7 shows how the functional effects can be translated from a qualitative text to a quantified functional index value, thus giving the impact level. These levels are consistent with the REMR Condition Index Scale (Table 1).

Function/Impact Matrix

82. A Function/Impact Matrix will be developed to automatically relate functional effect with impact level and produce a functional rating. Each functional effect and impact level may be given a weighting that, when multiplied together, would yield the functional rating.

83. It is important to note that this approach does not provide a quantification of a project's "worth"; that decision must be made at the national level according to the project's primary and secondary purposes.

Table 6
Functional Effects

Group 1

1. Reduced wave protection within the harbor/mooring area
 - a. Increased overtopping
 - b. Increased transmission through the structure
 - c. Increased reflection
 - d. Changed patterns of refraction/diffraction/shoaling
2. Reduced wave protection at the entrance/channel
 - a. Changed patterns of refraction/diffraction
 - b. Wave shoaling
 - c. Increased reflection
3. Increased sediment management needs
 - a. Scour patterns adjacent to structures
 - b. Sediment shoaling in navigation or mooring areas
 - c. Reduced natural sediment bypassing
 - d. Erosion of adjacent shores
 - e. Effect on sediment characteristics (grain size/quality)
4. Reduced navigational safety
 - a. Introduction of channel obstructions
 - b. Reduced navigability
 - c. Loss of navigation aids or rescue facilities

Group 2

1. Changed current velocities
2. Damage to vessels or facilities
3. Risk to public safety/access

Group 3

1. Environmental damage
 - a. Water quality
 - b. Loss of habitat
 - c. Degradation of esthetics
2. Adverse impacts on water levels in the harbor/mooring area
 - a. Modified hydrograph range
 - b. Storm surge trapping
 - c. Long-period oscillations
3. Erosion or flooding of harbor shores

Table 7
Impact Levels

Impact Level	Condition Index Range	Description
None	100	Action is not required, structure fully functional.
Minor	70-99	Immediate action not required. May have some minor impact on secondary function.
Moderate	40-69	Economic analysis of repair alternatives vs. benefits recommended to determine appropriate action. Only limited loss of primary function. Project still serviceable.
Major	0-39	Detailed engineering and economic analysis recommended to determine the need for repair or rehabilitation. Primary function has been seriously impaired or completely lost. Public safety or economic justification at risk.

PART V: A COASTAL STRUCTURE CONDITION INDEX

84. The final step in the rating process is to combine the structural and functional ratings to arrive at a CI number. Three basic concepts for this combination are presented here.

85. The first concept, illustrated in Figure 6, combines structural and functional ratings at the reach level to produce a CI value for each reach. The reach CI values would then be combined into a single CI value for the whole structure. (The formula for combining reach structural ratings, described in Part III, might be used.)

86. The second concept, shown in Figure 7, calls for structural ratings of each reach to be combined into a structural rating for the whole structure. At this point, the functional rating would be combined with the structural rating to produce a CI number for the whole structure.

87. The third concept, shown in Figure 8, uses the reach structural rating to help determine a reach functional rating, which leads to a reach condition index. The reach condition indexes are then combined into a single condition index for the whole structure.

88. It is anticipated that further development and refinement of the structural and functional rating procedures will lead to selection of the appropriate method for combining the two into CI values.

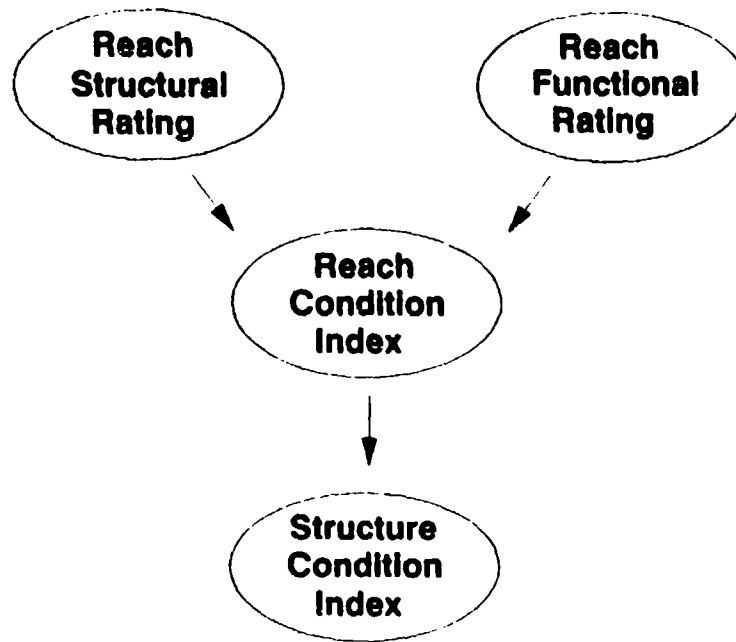


Figure 6. Concept 1 for determining condition index rating

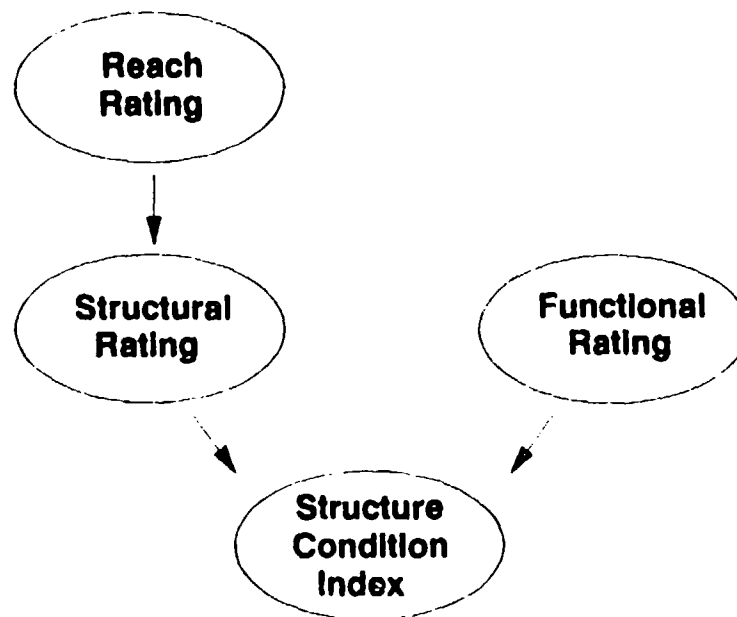


Figure 7. Concept 2 for determining condition index rating

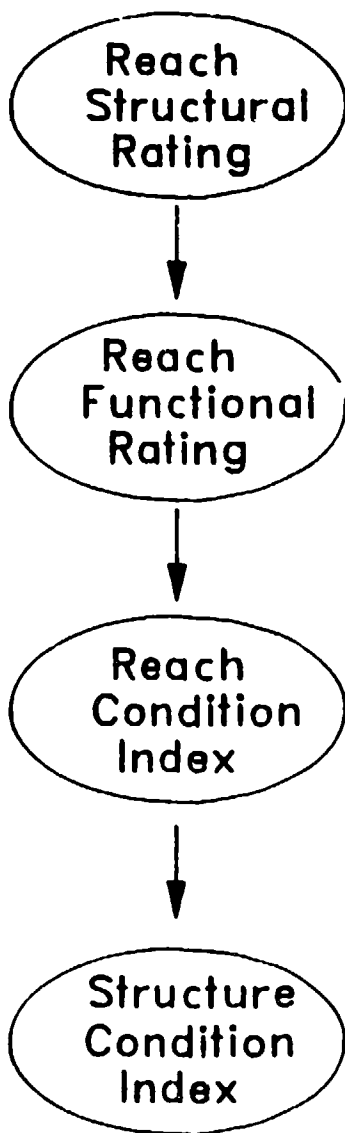


Figure 8. Concept 3 for determining condition index rating

PART VI: CONCLUSIONS AND RECOMMENDATIONS

89. The progress to date in the development of uniform, numerical, structural and functional rating procedures appears to indicate that, despite the difficulties encountered, such procedures can be created to provide a meaningful and useful method for describing structural condition. In addition, through the ratings produced at each stage in the process, several levels of detail will be available for managerial use.

90. Much work remains before the procedures are fully developed and refined, and substantial field testing and use by the Districts will be needed before the process is finalized.

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