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Repair, Evaluation, Maintenance, and Rehabilitation Research Program

REMR Program Overview and Guide

by William F. McCleese, Geotechnical Associates Networks, LLC

Prepared for Headquarters, U.S. Army Corps of Engineers

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Preface

The research reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program, Phases 1 and 2, conducted during fiscal years 1984-98.

Dr. Tony C. Liu was the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Dr. Liu and Mr. Harold Tohlen, CECW-O, served as the REMR Overview Committee. REMR Technical Monitors were Messrs. Jerry Foster, John Gilson, Mike Klosterman, M. K. Lee, John Lockhart, Jr., Arthur Walz, and Dave Wingerd of HQUSACE.

The REMR Program was managed at the U.S. Army Engineer Research and Development Center (ERDC) Structures Laboratory (SL) by Mr. William F. McCleese. General direction was provided by Dr. Paul Mlakar, Chief, Concrete and Materials Division, SL, and Dr. Bryant Mather, former Director, SL.

Problem Area Leaders were Messrs. D. D. Davidson, Jerry S. Huie, James E. McDonald, W. Milton Myers, and David R. Richards, ERDC, Vicksburg, MS, and Messrs. Al Beitelman and David McKay of the ERDC Construction Engineering Research Laboratory, Champaign, IL.

This report was prepared by Mr. McCleese (retired), under contract DACW39-99-P-0465 between Geotechnical Associates Networks, LLC, and the ERDC/SL. Contract monitor was Mr. McDonald, SL.

At the time of publication, Dr. James R. Houston was Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

Summary

The U.S. Army Corps of Engineers' Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program was conducted in two phases, beginning in fiscal year (FY) 1984. Phase 1 of the program was a 6-year, $35-million effort that was completed in FY 1989. This phase clearly demonstrated the benefits of research in getting more value for the dollars spent on REMR activities. The estimated dollar savings from the use of the research results exceeded $200 million over a 5-year period following completion of the Phase 1 effort.

Due to the successes of the Phase 1 effort and the opportunity for similar successes on other REMR-type problems, Phase 2 of the program was initiated in FY 1991 and was completed in FY 1998 at a cost of $31.2 million. The dollar savings from the use of the Phase 2 research results are estimated to be similar to those achieved from the Phase 1 research. Dollar savings attributed to use of REMR technology from both phases are expected to continue to accumulate for many more years.

The primary objective of the program was to identify and develop effective and affordable technology for maintaining and extending the service life of existing Corps civil works structures. For management purposes, the program was broken down into seven broad problem areas:

- Concrete and Steel Structures
- Geotechnical
- Hydraulics
- Coastal
- Electrical and Mechanical
- Environmental Impacts
- Operations Management

The report summarizes results of research in each of the seven problem areas and serves as a guide for accessing REMR technology.

1 Introduction

This report provides an overview and guide for accessing the technology products of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Comprehensive research results are available in 184 technical reports, *The REMR Notebook* with eight Supplements (173 Technical Notes), and 9 REMR video reports. There also exists a REMR Internet site (homepage at *http://www.wes.army.mil/REMR/remr.html*, which provides access to much of the REMR technology.

Program Development

The Corps of Engineers operates more than 600 hydraulic structures (lock chambers, flood control dams, powerhouses, etc.) at its civil works projects. About 70 percent of these hydraulic structures are over 20 years of age, 49 percent are more than 30 years old, and 26 percent were constructed prior to 1940. Approximately one half of the Corps' 269 lock chambers along inland waterways will have reached or exceeded their 50-year design-service life by the turn of the century. Additionally, the Corps of Engineers operates and maintains thousands of miles of roads, breakwaters, jetties, groins, dikes, revetments, levees, and floodwalls in its many civil works projects. Many Corps projects contain electrical and mechanical equipment that is subject to fatigue, wear, corrosion, and inefficiency.

One of the primary responsibilities of the Corps is to evaluate, maintain, repair, and rehabilitate these hydraulic structures. As a result of the 1972 National Dam Inspection Act (Public Law 92-367), greater emphasis has been placed on the evaluation and repair of the older hydraulic structures. Experience has shown that repair and rehabilitation of older facilities require various types of expertise, some of which are different from those required in connection with design and construction of the newer structures.

It is generally less expensive to maintain, repair, or even rehabilitate a structure than it is to build a replacement structure. Projected budgetary constraints in the 1980s meant that the Corps was faced with keeping many of the existing structures in operation well beyond their design-service life. As the age of a structure increases, so do its maintenance and repair needs. The Corps' operations and maintenance (O&M) appropriation had been increasing for more than a decade, and in the early 1980s it was approaching 50 percent of the total civil works budget.

Since such a large portion of the Corps' resources was devoted to maintenance and repair activities, it became obvious that research and development investments in this area provided an opportunity to obtain more value for the dollars being spent.

Funds were made available in fiscal year 1983 to conceptualize a comprehensive research program. In general, the deficiencies and needs that had been identified fell into three categories: the need for improved technology to quickly and accurately evaluate the existing condition of a Corps project; the need to maintain and repair projects in a cost-effective manner; and the need to lower the cost and time required to rehabilitate structures. The deficiencies and needs, along with recommended research, were summarized in the February 1983 "REMR Research Program Development Report," which was used to successfully seek funding approval for the program as a line item in the Corps' O&M budget.

The REMR Research Program was accomplished in two phases, from 1984 to 1998.

Objectives

The primary objective of the REMR Research Program was to identify and develop effective, affordable technology for maintaining and extending the service life of existing Corps civil works structures.

Although Corps needs were the driving force behind the research conducted, many of the results have application outside the Corps. Accordingly, another objective was to make REMR research results available to other Federal agencies, state and local governments, and the private sector. A comprehensive technology transfer program would thus serve to publicize research results to internal and external audiences.

Management Structure

Overall management of the REMR Research Program was provided by the Directorate of Research and Development. An Overview Committee was established at Corps Headquarters to scope and direct the program. A 12-member Field Review Group was formed to provide field input to the program and to assist with technology transfer to the field. A Program Manager, at the research laboratory level, provided day-to-day oversight of program activities and directed the technology transfer efforts.

REMR was a broad-based research program and, for management purposes, was divided into seven problem areas: Concrete and Steel Structures, Geotechnical, Hydraulics, Coastal, Electrical and Mechanical, Environmental Impacts, and Operations Management. A laboratory Problem Area Leader was designated for each of the problem areas to coordinate and manage the research within his respective area. A Problem Area Monitor from Corps Headquarters staff was appointed for each problem area to monitor the technical progress on each research study.

Use of REMR Overview and Guide

This overview and guide is provided as a tool to aid users in rapidly identifying and locating REMR technology that addresses specific subject areas. The technology is first categorized by the seven REMR Problem Areas and, further, by Subject Areas. The report's Contents listing can be used to choose a Subject Area of interest to the user. In this way, the user can navigate directly to the appropriate section(s) and view a summary of REMR technologies of most interest to him or her.

Each Subject Area section of Chapter 2 concludes with a listing of REMR reports and technical notes that provide detailed information on the technology and its use.

The *REMR Technical Notes* can be viewed, printed, or downloaded (in PDF format) from the REMR Internet site at *http://www.wes.army.mil/REMR/tn.html*. REMR Technical Reports can be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

2 Research Results

Concrete and Steel Structures

Research conducted under this problem area addressed three concerns: evaluation of the present condition of a structure (both above and below the waterline); maintenance, repair, and rehabilitation of concrete and steel structures; and surveillance and monitoring for structural safety. Results from research studies have been grouped into 23 Subject Areas, as summarized in the following sections.

In situ repair of concrete

Repair of concrete in hydraulic structures generally involves removing the deteriorated concrete and replacing it with new cast-in-place concrete. The objective of the research in this Subject Area was to identify materials and methods that would allow in situ treatment of deteriorated concrete without the need for removal. The initial step was a feasibility study to identify the types of deterioration most prevalent in concrete hydraulic structures, as well as the existing materials and methods commonly used for repair and rehabilitation. Once this information was collected, it was evaluated to determine the applicability of the various systems to the in situ repair of concrete hydraulic structures.

Of the repair techniques identified as being applicable to in situ repair, the pressure injection technique was selected for detailed evaluation (Figure 1). This procedure has been used extensively for repair of single, continuous cracks in structural concrete, but experience in pressure injection of mass concrete containing an internal network of multiple, interconnecting cracks had been minimal.

An in situ procedure was developed in the laboratory and demonstrated at Dam Nos. 20 and 13 on the Mississippi River. An evaluation of the concrete before and after injection indicated that the injection procedure worked well and the concrete areas injected were considered successfully repaired. Therefore, in situ repair of mass concrete seems to be a viable alternative to conventional concrete removal and replacement.

As a result of this research, the Rock Island District used pressure injection for rehabilitation of 38 tainter gate piers at Dam No. 20. Instead of removing and replacing the top 3.5 m (11 ft) of the pier stems as originally planned, only the top

Figure 1. A deep injection technique was demonstrated on a pier at Lock No. 13 on the Mississippi River

0.5 m (1.5 ft) was removed to allow replacement of the service bridge seats and to improve drainage on top of the piers. Pressure injection was used to rehabilitate the remainder of the structure. The cost savings attributed to the use of the in situ repair procedure at Dam No. 20 are $1.2 million.

Information was developed on the technique for deep injection of cracks in mass concrete and on the important properties of materials for injection into fine cracks.

Technology products:

Technical Reports REMR-CS-6, REMR-CS-11, REMR-CS-21, REMR-CS-30, and REMR-CS-48
Technical Notes CS-MR-3.9, CS-MR-3.11, CS-MR-3.12, and CS-MR-7.1

Continuous monitoring system for structural safety of large dams

The normal behavior of a dam needs to be understood so that abnormal behavior can be detected. Precise daily studies of dam motion were not previously feasible because the measurements could not be automated. Under this REMR research, a continuous monitoring system was developed that uses the Navstar Global Positioning System to determine three-dimensional differential movements at up to eight points on a structure. Each position is then compared to an original position to determine the total amount of movement. Accuracies of ±5 mm (0.2 in.) in the three dimensions are possible. The monitoring and data recording equipment is linked together with telephone lines, R-232 cable, or fiber-optic cable. No system operator is required, and real-time structural deformations can be monitored at a remote location such as a Corps district office. A prototype system was installed and demonstrated at Dworshak Dam in the Walla Walla District from July to September 1989.

Technology products:

Technical Report REMR-CS-39
Technical Note CS-ES-2.7

Rehabilitation of navigation lock walls

The general approach to lock wall rehabilitation has been to remove 30 to 91 cm (1 to 3 ft) of concrete from the face of the lock wall and replace it with new air-entrained concrete. One of the most persistent problems using this approach is cracking in the replacement concrete. A detailed numerical model study revealed that the cracking is due to the restraint provided by the large mass of concrete remaining in the lock wall. Shrinkage, during curing, of the resurfacing concrete is resisted by the existing concrete, and cracks develop.

It was postulated that, by using precast concrete as a stay-in-place form for the replacement concrete, cracking problems could be eliminated. A range of design alternatives were evaluated through a process of value engineering, and horizontal precast panels constructed of conventional precast quality concrete were selected for detailed quantitative investigation. The panels were designed to be tied to the lock monolith along the top and bottom edges using form ties to support the loads of the infill concrete placement (Figure 2).

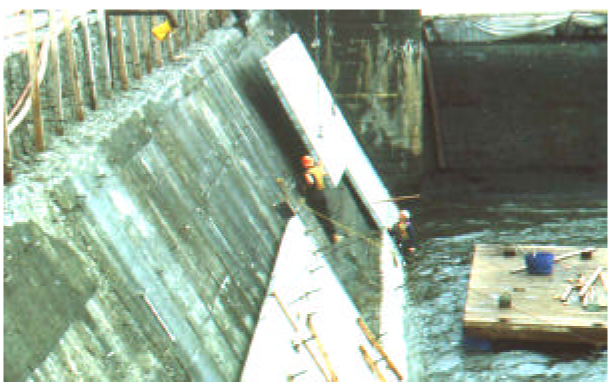

Figure 2. Precast forming system being used on the riverside wall of Troy Lock

Two one-half-scale lock-wall monoliths were used for a demonstration of the constructibility of this system and resulted in some minor design changes. The precast concrete stay-in-place forming system is a viable method for lock wall rehabilitation. In addition to providing a concrete surface of superior durability with minimal cracking, the estimated construction cost is about 15 percent less than conventional forming and concrete placement. Another advantage of the system is the potential reduction in the length of time that a lock must be closed to traffic during rehabilitation. With proper detailing, sequencing, and scheduling of work activities, the rehabilitation work may be accomplished with minimized impact on normal lock traffic.

Precast concrete panels were first used for the resurfacing of Lock No. 22 on the Mississippi River and Troy Lock on the Hudson River where $1 million in rehabilitation costs was saved by the use of this technology. The precast concrete stay-in-place forming system was also evaluated as a system that could be used for resurfacing lock walls without dewatering the lock chamber. This would allow the lock to remain operational. It could be closed for short periods to resurface one or two monoliths at a time and be opened for navigation between these periods. The details of this operation and the design for a barge-mounted cofferdam that would be used to dewater the work area are documented in the reports and videos listed below.

Technology products:

Technical Reports REMR-CS-7, REMR-CS-13, REMR-CS-14, REMR-CS-15, REMR-CS-28, and REMR-CS-41
Technical Notes CS-MR-1.13, CS-MR-8.1, CS-MR-8.2, and CS-MR-8.6
REMR Video Reports CS-2 and CS-4

Underwater surveying

The underwater portion of a concrete structure is often located in a hostile environment, making it difficult to assess the condition of the concrete. The objective was to provide information on accurate and inexpensive survey systems and techniques by which a comprehensive assessment can be made. As a part of this effort, a high-resolution acoustic-mapping system for performing rapid, accurate surveys of submerged horizontal surfaces was developed from jointly sponsored research with the Bureau of Reclamation. The system makes possible, without dewatering of the structure, comprehensive evaluation of top-surface wear on horizontal surfaces such as aprons, sills, lock chamber floors, and stilling basins where turbulent flows carrying rock and debris can cause abrasion-erosion damage (Figure 3).

Figure 3. Survey boat equipped with high-resolution acoustic mapping system

The high-resolution acoustic mapping system is now commercially available from Sonex, Ltd., in Richland, WA. It has been used successfully for underwater mapping at Chief Joseph and Ice Harbor, WA, and at Folsom Dam, Pine Flat, and Daguerre Point, CA. It can be used in water depths of 1.5 to 12 m (5 to 40 ft) and produces survey results with accuracies of 5 cm (±2 in.) vertically and 30 cm (±1 ft) laterally. The limitations of the system are that it can be used only in calm-water environments (a tilt of the survey vessel of more than 5 deg will cause the system to shut down), and it cannot pick up deep depressions less than 0.6 m (2 ft) in diameter. Information was also assimilated and published on underwater inspections, underwater cleaning tools, remotely operated vehicles, and short-pulse radar for underwater inspections.

Technology products:

Technical Reports REMR-CS-8 and REMR-CS-9
Technical Notes CS-ES-2.6, CS-ES-3.1, and CS-ES-3.2

Nondestructive testing

Nondestructive testing (NDT) of concrete allows the inspection of larger areas at less cost than coring and provides more information than a visual inspection. A comprehensive REMR technical report describes the available techniques, their applications, advantages, and disadvantages.

A new, improved prototype ultrasonic pulse-echo system was developed for the evaluation of concrete structures where only one surface is accessible. The system uses piezoelectric crystals for both signal generation and detection. The 200-kHz two-transducer system has a signal-to-noise ratio of 18. The weight and dimensions of the improved system have been reduced by 90 percent from the prior state-of-the-art system. The system, which has the shortest pulse length on record, works well in making thickness measurements of portland cement concrete (30 cm; <12 in.) and can indicate the presence of reinforcing steel, voids, and inferior-quality concrete both above and below water. The pulse-echo system was used in the development of a prototype NDT device called the SUPERSCANNER (Figure 4). By use of a moving pond of water as a coupler, the SUPERSCANNER can obtain continuous readings as it is towed over a concrete surface to detect delaminations and voids in the concrete.

To keep civil works metal structures fully functional and safe, a thorough inspection procedure must be implemented. A guide for the selection of an appropriate test method for metal structures was published. The guide includes information on the theory, applications, advantages, and disadvantages of each NDT method. Case histories are included which describe how NDT procedures can enhance inspection routines.

Technology products:

Technical Reports REMR-CS-10, REMR-CS-26, REMR-CS-40, REMR-CS-58, and REMR-CS-59
Technical Notes CS-ES-1.1, CS-ES-1.2, CS-ES-1.9, CS-ES-1.10, and EM-CR-1.4

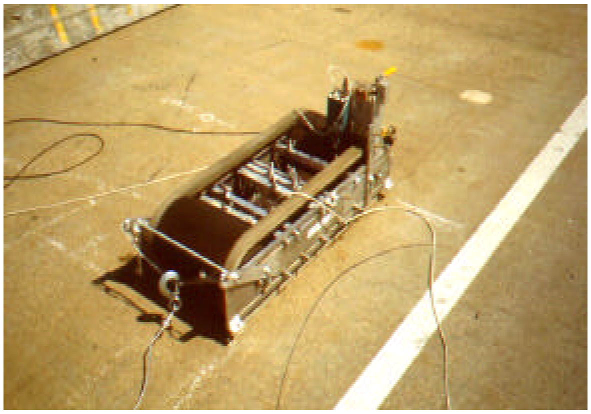

Figure 4. Prototype of SUPERSCANNER, which uses a moving pool of water as a coupler between transducers and the concrete surface. This coupling technique allows rapid nondestructive testing of the concrete as the device is towed over the concrete surface

Surface treatments to minimize concrete deterioration

Freezing and thawing, penetration of salts, weathering, chemical attack, and erosion cause concrete surfaces to deteriorate. Surface treatment of the concrete with a material more resistant to these forces than concrete can slow the rate of or even eliminate deterioration. Various surface treatments were evaluated with emphasis on materials that can reduce or prevent damage to concrete from cycles of freezing and thawing, the major contributing cause of non-air-entrained concrete failure (Figure 5).

Figure 5. Surface sealant being applied to a concrete surface

The test data for surface treatment materials indicate wide differences in the effectiveness of these materials for protecting concrete or minimizing concrete deterioration. Criteria were established for use as guidance in the selection of concrete sealers.

Technology products:

Technical Reports REMR-CS-17; Reports 1 and 2
Technical Notes CS-MR-4.2 and CS-MR-7.4

Underwater concrete repair

A large part of the cost of repairing the underwater portions of concrete structures is devoted to dewatering the structure so conventional concrete-placing techniques can be used. A review of the state-of-the-art techniques for concrete surface preparation underwater and underwater repair suggested that concrete could be effectively placed underwater by pumping when newly developed antiwashout admixtures were used and, thus, the dewatering cost could be eliminated.

Concrete mixtures were developed in the laboratory using these new admixtures to minimize the reduction in concrete quality that is normally associated with the placement of concrete underwater. In addition, several repair concepts (for example, use of precast elements) and various underwater concrete placement techniques (inclined tremie, pumping, etc.) were identified (Figure 6).

Figure 6. Laboratory tests of underwater concrete mixture using an inclined tremie

This technology is now widely used by the Corps, with significant cost avoidances by eliminating dewatering cost. One of the first applications was the repair of an eroded section of the end sill of the stilling basin at Red Rock Dam, Iowa. The use of an underwater concrete mixture pumped underwater to the repair area resulted in estimated savings of $700,000 from elimination of the need to dewater the stilling basin. This REMR technology was also used to plug the service tunnel under Chicago in April 1992, when the Chicago River flooded the tunnel.

Additional research on underwater concrete mixtures is being conducted under the Corps' Innovations for Navigation Projects (INP) Research Program. For the latest information, visit the INP homepage at http://www.wes.army.mil/ INP/inp.html.

Technology products:

Technical Reports REMR-CS-18, REMR-CS-19, REMR-CS-34, and REMR-CS-37
Technical Notes CS-ES-3.3, CS-ES-3.4, CS-ES-3.5, CS-ES-3.6, CS-ES-3.7, CS-MR-7.2, CS-MR-8.1, CS-MR-9.3, and CS-MR-9.4
REMR Video Report CS-3

Instrumentation automation for concrete structures

Automation of instrumentation at existing concrete structures can increase the timeliness and accuracy of data and can reduce man-hour requirements. It can also permit the instruments to be monitored from a remote location or from a Corps district office. Information was accumulated on commercially available hardware and software, and guidance was developed on the use of these products for instrumentation automation.

This technology was demonstrated at Beaver Dam near Eureka Springs, AR, where pressure cells, weirs, joint meters, and piezometers were automated (Figure 7). Prior to the automation of the 84 piezometers, it took a team of field personnel 4 hr to read the piezometers that can now be read in less than a minute.

Figure 7. Automated piezometers at Beaver Dam, AR

Technology products:

Technical Reports REMR-CS-5; Reports 1, 2, 3, 4, and 5
Technical Notes CS-ES-2.1, CS-ES-2.2, and CS-ES-2.3

Maintenance and repair materials database

The number of commercially available materials touted for maintenance and repair of concrete and steel structures is enormous and continues to grow. It is difficult to select an appropriate material among the large number of products available and to evaluate product manufacturers' claims on the applicability of their products to maintenance and repair problems. To assist personnel in the selection of materials, a maintenance and repair materials database was developed and was first made available for accessing by remote computer terminal.

An expert system was developed to aid in selecting repair materials for specific applications. Access to the materials data sheets on materials tested at the Waterways Experiment Station can be obtained from the REMR homepage at http://www.wes.army.mil/REMR/remr.html. Maintenance and upgrading of the database are expected to continue under the High-Performance Materials and Systems Research Program (http://www.wes.army.mil/HPMS/hpms.html).

Technology products:

Technical Report REMR-CS-27

Concrete joint repair

Joints in concrete hydraulic structures tend to deteriorate faster than other parts of the structure and are more difficult to repair, especially if they are leaking water. Many materials and techniques have been used to repair joints, with the majority of them lasting only a short time. The lack of an appropriate test procedure that would allow laboratory evaluation of these materials and techniques resulted in expensive and often unsuccessful prototype applications.

Under the REMR Program, a case histories report on joint repairs was published, and a unique laboratory apparatus (Figure 8) was designed and built for testing materials and techniques in the laboratory under the environmental conditions they would face in a prototype application. This apparatus can also be used to test crack repair procedures for cracks that are leaking or flowing water with up to 30 m (100 ft) of head. Several materials were tested in the apparatus under various water heads and joint movements to simulate seasonal movements. Test results are available in *The REMR Bulletin* (Vol 14, No. 1, February 1997) and can be accessed from the REMR homepage at http://www.wes.army.mil/REMR/ remr.html.

Technology products:

Technical Report REMR-CS-22
Technical Note CS-MR-8.7

Figure 8. Laboratory joint and crack repair test apparatus

Geomembrane repair system

The application of geomembranes to the upstream face of leaking and deteriorated concrete dams in Europe has been so successful that these systems are considered competitive with other repair alternatives in terms of durability and costs. However, the geomembranes were typically installed in a dry environment by dewatering the structure on which the system is to be installed. Dewatering can be extremely expensive and, in many cases, may not be possible because of project constraints. Therefore, a procedure for underwater installation of geomembrane repair systems was developed.

In Phase I, a conceptual design for the underwater repair system was developed. The constructibility of the design was demonstrated in Phase II through successful underwater installation of the system on a simulated concrete structure. The underwater demonstration of the innovative geomembrane repair system is documented. Compared to dewatering of a structure for repair, a geomembrane system that can be installed underwater minimizes the impact of the repair on project operations such as hydropower generation and recreation. Also, the underwater repair system eliminates the potentially adverse environmental impacts associated with dewatering of many structures. The system offers the flexibility for application to the entire upstream face of a dam or can be limited to a leaking crack or joint. It also offers a permanent solution to troublesome leaks in intake towers.

The first application of this technology was at Lost Creek Dam (Figure 9) in California in 1997. The dam owner (Oroville-Wyandotte Irrigation District) claims it saved over $2.8 million on life-cycle cost by selecting the geomembrane solution over other rehabilitation alternatives.

Technology products:

Technical Reports REMR-CS-50 and REMR-CS-51
REMR Video Report CS-5

Figure 9. Lost Creek Dam being rehabilitated by the use of a geomembrane applied to the upstream face of the dam without dewatering the reservoir

Grouting of anchors in concrete

Rehabilitation of hydraulic structures usually includes removal and replacement of deteriorated concrete. Dowels are normally used to anchor the new concrete to the existing concrete and to position vertical and horizontal reinforcing steel in the replacement concrete. A REMR study was conducted to evaluate the effectiveness of cement, epoxy, and polyester resin grouts used to embed reinforcing steel bars in hardened concrete under a variety of placing and curing conditions (Figure 10).

Figure 10. Laboratory test of a technique for installing concrete anchors underwater using a vinylester resin capsule

Many repairs are now being made underwater to eliminate dewatering cost and, therefore, the performance of anchors grouted under submerged conditions was evaluated. A technique, using a vinylester resin, was developed which provides good results for the grouting of anchors under submerged conditions.

Technology products:

Technical Reports REMR-CS-20, REMR-CS-23, REMR-CS-33, and REMR-CS-56
Technical Notes CS-MG-1.1 and CS-MG-1.2

Repair of brick and masonry walls

The Corps of Engineers is responsible for the upkeep of thousands of brick and stone masonry structures in its building inventory. Many of these structures have strong historical significance to the country. Repair and maintenance of these structures are important components in managing Corps property and preserving the nation's historical heritage. Proper execution of repair and restoration techniques in rehabilitating these structures will ensure that they endure and remain useful for many years.

Case histories of repair and restoration to damaged brick and stone masonry structures were documented to present many acceptable repair and restoration techniques in use today. In several cases, additional research information on repair techniques and repair goals was provided to supplement the data on the repair. The case histories were chosen to give a broad review of different types of deterioration to brick and stone masonry construction and the chosen solutions. The cases reviewed cosmetic restorative work as well as structural restoration and structural upgrading to earthquake-resistance standards.

Technology products:

Technical Report REMR-CS-46
Technical Notes CS-MR-4.1, CS-MR-4.3, CS-MR-4.4, and CS-MR-9.5

Performance criteria for concrete repair materials

The durability of concrete repairs depends to a large extent on the proper selection and application of repair materials. Restrained contraction of repair materials, the restraint being provided through bond to the existing concrete substrate, is a major factor that significantly increases the complexity of repair projects as compared to new construction. Other factors include coefficient of expansion, modulus of elasticity, early age tensile strength, and creep properties of the repair material.

A study was conducted to develop performance criteria for cement-based repair materials. Results of laboratory tests and field performance studies were correlated, and guidance for selection of repair materials that would reduce the risk of premature failures was developed. This guidance includes a standard protocol for repair material data sheets and proposed performance criteria. While there was a general correlation between the results of laboratory tests on unrestrained shrinkage specimens and field performance, there is a need for restrained shrinkage tests to evaluate the cracking resistance of repair materials. Although there was a general lack of significant correlation between individual material properties and field performance, results indicate that it is possible to predict the field performance of repair materials based on a combination of material properties determined in laboratory tests.

Results emphasize the need for a comprehensive analytical model to predict the cracking resistance of repair materials that considers the interrelationship of pertinent material properties, the relative importance of individual properties, and the effect of environmental conditions on time-dependent material properties.

Technology products:

Technical Reports REMR-CS-12, REMR-CS-47, REMR-CS-52, REMR-CS-57, REMR-CS-60, REMR-CS-61, and REMR-CS-62

Repair and rehabilitation of dams

Roller-compacted concrete (RCC) can be an economical alternative to anchors in stabilization of dams and can be used to repair overflow structures and to protect embankment dams during overtopping. The potential of RCC in repair and rehabilitation of dams was evaluated (Figure 11), and case histories were compiled to illustrate the versatility of RCC in repair, rehabilitation, and replacement of hydraulic structures. RCC applications include increasing existing spillway capacities; construction of new service, emergency, and combination spillways; repair of spillways, outlet tunnel, and lock floor; and overtopping and scour protection for rock fill timber crib, earth fill embankment, and concrete dams. The in-place cost of RCC is about 40 percent of the in-place cost of conventional concrete.

Figure 11. Roller-compacted concrete was used to rehabilitate this overflow dam (Ocoee No. 2 Dam, Tennessee)

Research was also conducted to develop, review, and analyze applications of precast concrete in the repair or replacement of civil works structures (Figure 12). Information was obtained through literature searches; discussions with designers, precasters, and contractors; visits to project sites; and discussions with project personnel. Each case history includes a description of the project, the cause and extent of the deficiency that necessitated repair or replacement, design details, descriptions of materials and precasting procedures, construction techniques, costs, and performance to date of the precast concrete.

Figure 12. Precast concrete was used for this wing wall at Melvin Price Dam

Based on a review and analysis of these case histories, recommendations for future applications of precast concrete were developed, and areas that could benefit from research were identified. Compared with cast-in-place concrete, precast offers the advantages of rapid construction, low unit cost through mass production, and high quality, durability, and mobility.

Selected repair efforts to intake structures and conduits were also documented in a case history format that includes a project description and a history of the repair efforts.

Technology products:

Technical Reports REMR-CS-1, REMR-CS-16, REMR-CS-38, REMR-CS-49, REMR-CS-53, and REMR-CS-55
Technical Note CS-MR-7.3

Remedial waterstops

Nearly every concrete structure has joints that must be sealed to ensure its integrity and serviceability. This is particularly true of monolith joints in hydraulic structures such as concrete dams and navigation locks. Embedded waterstops are generally used to prevent water passage through the monolith joints of such structures. A waterstop failure can result in various problems, ranging from minor leakage with cosmetic concern to significant hydraulic forces and structural overloading that could threaten the stability of a structure.

A study was conducted to identify materials and techniques used in the repair of waterstop failures, and to determine their degree of success. (Related information is given in the Subject Area sections entitled Concrete joint repair and Geomembrane repair systems.)

Technology products:

Technical Report REMR-CS-4
Technical Note CS-MR-8.8
REMR Video CS-1

Abrasion-erosion and cavitation-erosion repair

Silica fume offers potential for improving many properties of concrete. However, the very high compressive strength and the resulting increase in abrasion-erosion resistance are particularly beneficial in repair of hydraulic structures. These concretes should be considered in repair of abrasion-erosion susceptible locations, particularly in those areas where locally available aggregate might not otherwise be acceptable. The potential for cracking of restrained concrete overlays, with or without silica fume, should be recognized. Any variations in concrete materials, mixture proportions, and construction practices that will minimize shrinkage or reduce concrete temperature differentials should be considered.

Guidance on corrective actions and selection of repair materials for abrasion-erosion and cavitation-erosion were documented.

Technology products:

Technical Report REMR-CS-32
Technical Notes CS-MR-9.1 and CS-MR-9.2

Evaluation and repair of hydraulic steel structures

Steel components such as lock gates, miter gates, and tainter gates are critical to the successful operation of hydraulic structures. These components are subject to corrosion, fatigue, wear, and impact damage. Studies were conducted under the REMR Program to provide guidance on the evaluation, repair, and reliability of these steel components. Nondestructive testing methods were identified, and structural evaluation tools were developed. Evaluation and repair procedures for fatigue cracks were developed.

Study results were used to develop a new design for navigation lock lift-gates that have a fatigue life twice that of the old designs. This design was used for the replacement gates at Mississippi River Locks 27, with estimated life-cycle cost savings of $1.7 million.

Technology products:

Technical Reports REMR-CS-24, REMR-CS-31, REMR-CS-43, REMR-CS-44, and REMR-CS-45
Technical Notes CW-ES-1.3, CS-ES-1.4, CS-ES-1.5, CS-ES-1.6, CS-ES-1.11, CS-ES-1.12, CS-ES-2.4, CS-ES-2.5

Predicting concrete service life

A probabilistic procedure was developed for predicting the service life of concrete structures subject to damage due to freezing and thawing and was applied to two typical Corps civil works structures. These hindcast applications demonstrate the procedure and provide results encouragingly comparable to observed deterioration. The sensitivity of the results to key material and environmental variables is discussed. Current testing procedures relevant to service life prediction are discussed, along with recommendations for improvements in these areas.

Technology products:

Technical Report REMR-CS-35
Technical Note CS-ES-2.8

Evaluation of concrete by other than NDT methods

Several REMR Technical Notes were developed to provide guidance for the evaluation of concrete. These include "Petrographic Examination of Distressed Concrete," "Water Absorption and Water Vapor Transmission Testing," and "Site Inspection and Sampling Concrete Damaged by Alkali-Silica Reaction."

Technology products:

Technical Notes CS-ES-1.7, CS-ES-1.8, and CS-ES-1.13

Concrete removal techniques

Most concrete repairs require some removal of deteriorated or damaged concrete. Several procedures are available for removal of concrete above and below water (Figure 13). The procedure chosen should permit efficient and cost-effective concrete removal yet minimize the damage (microcracking) of the concrete that

Figure 13. A concrete diamond saw was used to remove concrete for modifications to Marseilles Dam, Rock Island District

remains. Technology products of this research provide users with descriptions of the available techniques and information on selecting an appropriate removal technique. Guidance was also developed to establish concrete removal limits.

Technology products:

Technical Notes CS-MR-1.1, CS-MR-1.2, CS-MR-1.3, CS-MR-1.4, CS-MR-1.5, CS-MR-1.6, CS-MR-1.7, CS-MR-1.8, CS-MR-1.9, CS-MR-1.10, CS-MR-1.11, CS-MR-1.12, CS-MR-1.14, and CS-MR-2.1

Concrete crack repair

Successful repair of cracks in concrete depends upon identifying the cause of the crack and selecting a repair method or methods (Figure 14) that will take the cause into account. Conditions that can cause cracks were identified, along with a general guide to whether the crack being considered will remain "active" or "dormant." Active cracks are defined as those for which the mechanism causing the cracking is still at work. (Any crack for which an exact cause cannot be determined is considered to be active.) Dormant cracks are those caused by a condition that is not expected to recur.

Figure 14. Gravity soak method of concrete crack repair using a very low viscosity resin

Guidance on the selection of a crack repair method and information on the various repair methods, along with their applications and limitations, are provided in several *REMR Technical Notes*.

Technology products:

Technical Notes CS-MR-3.1, CS-MR-3.2, CS-MR-3.3, CS-MR-3.4, CS-MR-3.5, CS-MR-3.6, CS-MR-3.7, CS-MR-3.8, CS-MR-3.9, CS-MR-3.10, CS-MR-3.11, and CS-MR-7.1

Overlays on horizontal concrete surfaces

Bonded overlays have been used for decades as a means to rehabilitate horizontal concrete surfaces that have deteriorated. The earlier overlays were conventional concrete mixtures that were solely portland cement based. Over the years, other materials (such as air-entraining, water-reducing, and polymeric admixtures, fly ash, silica fume, and fibers) were employed in an effort to improve the durability of the overlay and reduce the penetration of chlorides into the subjacent concrete. The resulting overlays included low-slump, fly ash, silica fume, polymer-modified, polymer, and fiber-reinforced concretes. For some nonstructural repairs, unbonded overlays have been employed to reduce reflective cracking and cracking resulting from the restrained contraction of the concrete overlay by the subjacent concrete. Overall, the performance and cost-effectiveness of these various overlays are varied and unclear.

Case studies revealed the following information. Shrinkage and reflective cracks that develop in polymer-modified concrete overlays and overlays containing polypropylene fibers are more likely to be smaller in width and length than those of similar cracks in conventional and low-slump concrete overlays. Cracks in concrete containing fibers are generally smallest. Cracks that exist at corners of blockouts and other changes of geometry in the original concrete will likely be reflected in the bonded overlay. The location of these cracks can be controlled via employment of dummy joints. Unbonded overlays typically have less frequent and smaller cracks than bonded overlays.

Technology products:

Technical Report REMR-CS-42

Geotechnical

Primary concerns under the geotechnical problem area were remedial treatments for foundation and seepage problems.

Improvement of foundation soils susceptible to liquefaction

Liquefaction of foundation soils can cause catastrophic failure or limit the usefulness of a project. It is now known, through new and improved testing procedures, that many Corps structures are located on liquefiable foundations.

Techniques applicable for remedial treatment of the foundations of existing structures were identified, and guidance was provided for their selection and use.

Two of the more promising techniques are sand compaction piles and stone columns. The relative costs of these techniques are moderate, and they provide vertical support, drains to relieve pore water pressure, and shear resistance in horizontal and inclined directions. Stone columns (Figure 15) were used to improve foundation conditions at Steel Creek Dam, Georgia, and sand compaction piles were used by the Pacific Ocean Division to improve foundation conditions on two military projects in Japan.

Technology products:

Technical Reports REMR-GT-4 and REMR-GT-7
Technical Note GT-SR-1.2

Figure 15. Equipment used to install stone columns for improvement of foundation conditions

Restoration of relief wells

Relief wells, a safety feature when installed at a structure, can become clogged by chemical or biological encrustation, allowing uplift pressures to increase beneath the structure. A procedure was developed for restoring the efficiency of these wells using a process called Blended Chemical High Temperature or BCHT (Figure 16). The Corps has approximately 5,000 relief wells that must be treated periodically or replaced. The BCHT process extends the maintenance interval for these wells by at least 1 year with annual savings of $500,000.

An example of additional savings is the relief wells at the New Alton Pumping Station Project in the St. Louis District. Standard cleaning methods failed to bring these wells up to the required 80 percent of original capacity. The BCHT process was demonstrated to be capable of successfully cleaning the wells, thus eliminating the expense of replacement wells. The cost difference between restoration and possible replacement of as many as 60 wells at this site was estimated to be $1.5 million.

Figure 16. One of the steps in the BCHT process is flushing the well after chemical treatment

Minimum-maintenance procedures were developed which use cold mixed chemicals and can be used to extend the treatment period between major restorations. Guidelines were developed for chemical use, including the dispersal phase where the well is flushed and the effluent can move into streams.

Technology products:

Technical Reports REMR-GT-16 and REMR-GT-18

Control of adverse levee underseepage

Underseepage control measures designed and constructed according to established criteria had proven inadequate at many sites. Improved guidelines were developed for special foundation conditions and levee alignments. Computer programs were developed that allow the user to evaluate various remedial alternatives for controlling adverse levee underseepage and estimate the construction costs of these alternatives. The developed programs allow analyses that are not restricted to the boundary conditions assumed in the conventional closed-form solution, that is, two foundation layers of uniform thickness with horizontal boundaries. Guidance was also developed for inspection and control of levee underseepage during flood conditions.

Technology products:

Technical Reports REMR-GT-5, REMR-GT-11, REMR-GT-13, and GL-89-13

Computer codes LEVEE3L, LEVEEIRR, LEVEECOR, and LEVEEMSU are available from the U.S. Army Engineer Research and Development Center/Geotechnical Laboratory, Vicksburg, MS.

Stability of existing concrete gravity structures on rock

Reevaluations of several aging concrete gravity structures revealed that many of these structures did not meet the Corps' stability criteria for new structures. Even though these structures had performed well for many years with no sign of instability, the response was to strengthen these structures by the use of anchors, a very expensive endeavor. REMR research results showed that the stability criteria used for these existing structures was overly conservative. The Corps' stability criteria for existing concrete gravity structures was changed based on research results. The revised criteria use a three-phased approach that, when justified by site conditions, allows reduction of earth pressures and credit for shear stresses that develop in the backfill as deformations occur. Also, when the remaining service life is short and the consequences of failure are not severe, the minimum factor of safety can be relaxed somewhat for different loading conditions. The revised criteria resulted in the avoidance of unnecessary and expensive structural rehabilitation for many of the Corps' concrete gravity structures.

In fiscal year 1987, this research was used by Corps Headquarters to conclude that Eisenhower and Snell Locks on the St. Lawrence Seaway were structurally stable. The result was a cost avoidance of between $14 and $17 million. Another example of savings resulting from this research is Troy Lock and Dam in the New York District. Troy Lock and Dam did not meet the old stability criteria and was being considered for structural rehabilitation. When the revised criteria were applied, Troy was found to meet the criteria, and structural rehabilitation was not performed. The savings resulting from the elimination of unnecessary anchoring work are estimated to be $3 to $4 million.

Technology products:

Technical Reports REMR-GT-12, REMR-GT-14, REMR-GT-20, REMR-GT-21, REMR-GT-22, and REMR-CS-54
Technical Notes CS-ES.4.1, CS-ES-4.2, CS-ES-4.3, CS-ES-4.4, CS-ES-4.5, CS-ES-4.6, CS-MR-8.3, CS-MR-8.4, CS-MR-8.5, GT-RE-1.2, GT-RE-1.4, GT-RE-1.5, GT-RE-1.6, and GT-RE-1.7

Remedial cutoffs and control methods

Seepage related to embankment dams can be a serious problem, and remedial control methods are limited and expensive. Laboratory tests and guidance were developed for determining when seepage is a serious problem and is likely to lead to severe damage of the structure. Corps dams located within glacial regions where widely graded soils may have been used as core materials were inventoried. Mud Mountain Dam, Washington, was selected as the prototype project for this study, and research to determine the erosion characteristics of the core material yielded a modified "No Erosion Filter Test." This test can be used to determine whether the chimney drain material is adequately sized to seal any cracks that may develop in the core material of the dam.

Guidance was developed on recently developed remedial seepage control methods, such as plastic concrete cutoff walls, reinforced earth berms, and jet-grouted cutoff walls (Figure 17).

Figure 17. Jet grouting equipment can be used for installing cutoff walls

Technology products:

Technical Reports REMR-GT-5, REMR-GT-11, REMR-GT-13, and REMR-GT-16
Technical Notes GT-SE-1.3, GT-SR-1.2, and GT-SR-1.3

Expert system for remedial seepage control

Leakage and underseepage are continuing problems at many Corps structures. An expert system was developed for diagnosing seepage problems associated with earth, rockfill, concrete, and roller-compacted concrete dams. The user is prompted for a description of his problem, given a diagnosis, and presented with some possible remedial actions. The user may also link, via the expert system, to a database containing case histories of dams maintained by the U.S. Army Corps of Engineers. Each of the dams in the database has had one or more seepage problems. The case histories can be accessed by problem type (wet spots, abnormally high piezometric readings, turbid seepage, etc.) and thus provide the user with information concerning ways in which seepage problems similar to the one at hand have been solved.

Technology products:

Technical Report REMR-GT-19

Allowable movements and performance criteria

A major deficiency existed in the ability to evaluate the need for remedial measures for structures that are undergoing continuing movements, and in the ability to predict or verify the effectiveness of remedial measures. Design and analysis methods for newer structures do not predict or provide useful criteria for tolerable movements of older structures.

A computational procedure capable of predicting failure mechanisms in earth structures was developed. This valuable new tool is important because it ties the stability of a structure to displacements that can be observed in the field and provides a method for evaluating the effectiveness of remedial measures.

The analysis procedure has been developed into a comprehensive computer code for two-dimensional analysis of soil-structure interaction and embankment problems. It was first used to analyze allowable movements for sheet-pile I walls for the New Orleans District. The results showed that it was not feasible to limit wall movements by use of expensive, stiff sheet-pile sections and excessive sheet-pile lengths, as prescribed by existing design criteria. An alternative design criterion, which accommodates larger movements, was adopted. Estimated savings of $7.4 million were achieved by applying this technology to the design of sheet-pile I walls at the Orleans Outfall Canal, 17th St. Outfall Canal, West Wego to Harvey Canal, New Orleans to Venus Canal, and St. Charles Parish Levee in New Orleans, LA.

Technology products:

Computer code SOILSTRUCT is available from the U.S. Army Engineer Research and Development Center/Geotechnical Laboratory, Vicksburg, MS.

Grouting for foundation repair and rehabilitation

Foundation grouting has long been an accepted procedure for improving foundation conditions. The objective of this effort was to evaluate and develop modern methods of foundation grouting to improve quality control and reduce costs.

Several products were developed under this effort, including a comprehensive technical report on consolidation grouting of rock masses.

A computerized grout control and monitoring system was developed under a joint effort with the Bureau of Reclamation. The use of this system is expected to substantially reduce the number of changed condition claims by grouting contractors.

A method to evaluate rock properties prior and subsequent to grout injection was developed. A drill rig instrumented with a drilling parameter recorder is used to predict groutability (Figure 18), and an acoustic emission monitoring system is used for mapping grout location. Test grouting on this method was conducted at Little Dell Dam, Utah.

Technology products:

Technical Reports REMR-GT-8
Technical Note GT-RR-1.1
REMR Video Report GT-1

Figure 18. Drill rig instrumented with "Drilling Parameter Recorder"

Rock erosion in spillway channels

Until this research effort, the Corps did not have a technically sound method for predicting the rate of erosion on unconsolidated indurated or semi-indurated materials that exist in many spillway channels. An understanding of the combined effects of the geometry, pressure differentials, and velocity was used to develop guidance for predicting erosion potential of high-level emergency spillways. This guidance can be used for judicious decision-making concerning operation and maintenance (O&M) expenditures for remedial treatments.

Significant progress was made in understanding the headward erosion that has been observed in unlined emergency spillways in rock. Model studies showed that headward erosion is most severe when an air pocket exists below the overflow nappe at below-atmospheric pressure. This pulls the plunging water closer to the toe of the knickpoint where severe erosion occurs, and causes the knickpoint to move upstream. Venting the air pocket results in the overflow shooting farther from the toe of the knickpoint, and results in less erosion and a slower upstream migration of the knickpoint. The application of this technology in critical flow situations could very well prevent the loss of a reservoir impoundment and the severe flooding that would occur from such an event.

An understanding of the mechanics of spillway channel erosion was used to develop remedial treatment technology for problem spillways. This technology was used to develop remedial treatment plans for the Saylorville Spillway, Iowa, which resulted in significant dollar savings over the cost of lining the spillway (Figure 19). It was also used for the repair of the emergency spillway at Painted Rock Dam, Arizona.

Figure 19. Inspection of Saylorville Spillway, Des Moines, IA, following an overflow event

A supplemental report addresses the geologic factors that control rock erosion, develops a technique to evaluate risk and predict the potential erosion of rock and soil exposed to hydraulic attack during a flow event in the channel, and provides design concepts for the repair and rehabilitation of spillway erosion.

Technology products:

Technical Reports REMR-GT-3, Reports 1, 2, 3, 4, 5, and Supplemental Report
Technical Notes GT-RE-1.1, GT-RE-1.3, GT-SE-1.1, and GT-SE-1.2

Geophysical techniques

Existing structures complicate and limit routine application of standard engineering geophysical techniques for foundation assessments.

Field procedures, data-processing methods, and interpretation methods were developed or adapted for high-resolution seismic reflection, ground penetration radar (GPR), microgravity, and self-potential methods.

Two field test sites were selected, and the methods were applied to assess various structure and foundation problems. At the Lockport Approach Dike on the Illinois Waterway, near Joliet, IL, a GPR survey detected possible seepage paths through the dike, verified the location of the concrete core wall, and assessed its condition. At Dike 1, Beaver Dam, Arkansas, a comprehensive foundation assessment was conducted (Figure 20). The geophysical methods applied at Dike 1 succeeded in mapping seepage paths and delineating the complex geology. Based on the results of the geophysical surveys and other geotechnical investigations, the rational design of a concrete cutoff wall to eliminate anomalous seepage was possible.

Figure 20. Results from geophysical studies were used to design a concrete cutoff wall at Beaver Dam, Arkansas

During this research, the technology was applied to two sites under other funding. A GPR survey was conducted at the Tomb of the Unknown Soldier in Arlington Cemetery, and a microgravity survey was conducted in the Great Pyramid of Cheops, Giza, Egypt. The Tomb is an existing structure of great national and patriotic significance, while the Great Pyramid is one of the oldest existing structures built by man.

REMR technology was also applied in a comprehensive assessment of the foundation of Mill Creek Dam near Walla Walla, WA. In this assessment, researchers mapped major anomalous zones in the foundation, which contributed to the planning for remedial measures.

Technology products:

Technical Reports REMR-GT-6, Reports 1, 2, 3, and 4;
REMR-GT-9; and REMR-GT-10

Cost-effective shoreline erosion control

Shoreline erosion often threatens critical resources and real property at Corps reservoirs, many of which are eroding at alarming rates. At least 60 percent of Corps reservoir shorelines are threatened with erosion, and over 10,000 Corps reservoir miles are estimated to have moderate to serious erosion. Conventional structural approaches to erosion control (e.g., revetted riprap or bulkheads) are expensive, not always necessary, and sometimes incompatible with environmental objectives.

New cost-effective concepts for reservoir shoreline erosion control were investigated and demonstrated (Figure 21). Guidance was developed for selecting, designing, and constructing biotechnical and low-cost structural erosion control at reservoirs.

Figure 21. A low-cost, biodegradable, floating breakwater being installed to protect flood-tolerant vegetation planted on the shoreline until it is established

An example of the application of this technology was its use on 300 m (1,000 ft) of shoreline at Eufaula Lake, Oklahoma. The application was a success, and the cost was about one fifth that of traditional riprap protection. The resulting cost savings was $200,000.

Technology products:

Technical Notes GT-SE-1.5 and GT-SE-1.6

Water Quality Bulletin (Vol 1, No. 1, July 1999), "Reservoir erosion control and revegetation workshop and demonstration, Smithville Lake, Missouri"

Innovative levee rehabilitation methods

The Corps of Engineers is responsible for 8,500 miles of levees. Levees are subject to overtopping, current and wave attack, surface erosion due to rainfall, through-seepage, underseepage, and slope instability. Conventional methods of levee rehabilitation are both costly and time consuming.

New methods of levee rehabilitation were identified and investigated (Figure 22). Analytical studies were conducted on two-dimensional slope stability analysis of geogrid-stabilized slides and on slope remediation using a prefabricated geo-composite drainage system. Laboratory studies were conducted to determine the effectiveness of short randomly distributed polypropylene fibers in reducing crack development (and shallow surface sliding) in clay slopes. Guidelines were developed for applying innovative chemical and physical techniques such as geosynthetic systems, mechanically stabilized soil, soil nailing with geotextiles, gravel trenches, and slide suppressor walls to levee rehabilitation. The use of innovative rehabilitation methods can result in savings of up to 50 percent over conventional techniques at some sites.

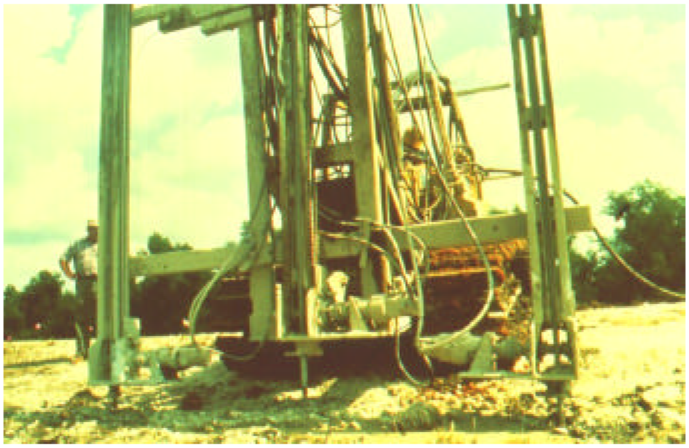

Figure 22. Lime-fly ash injection into a Mississippi River levee at Sikeston, Missouri

Technology products:

Technical Reports REMR GT-23, REMR-GT-24, REMR-GT-25, REMR-GT-26

Unnumbered Report, “Proceedings of REMR Workshop on Levee (August 1994)

Technical Notes GT-SE-1.7 and GT-SE-1.8

Stone degradation and performance prediction

Studies on stone protection material by all the Corps district and division engineers indicate that there is a significant difference between assumed stone durability and the actual service life of stones. An accurate method of stone degradation prediction—based on a review of existing testing procedures, field verification of stone performance, and development of new field and laboratory testing procedures—was investigated.

An approach for evaluating the durability of rock for use as riprap was developed. This approach is applicable for use by geologists in stone selection and by construction site inspection personnel for acceptance/rejection of stone. A stone evaluation system (Figure 23) was developed which is based on four tests that probe the candidate rock for structural defects that may serve as pathways for fluid imbibition and sites for mechanical fracture/failure. Test results are entered into a classification table that provides an indication of a stone’s durability.

Technology products:

Technical Report REMR-GT-26

Figure 23. The actual service life of stone is often significantly different from what was predicted

Hydraulics

Under the hydraulics problem area, investigations were conducted on ways to minimize scouring problems and to improve navigation conditions and operational capabilities.

High-level emergency spillways

The Corps has numerous high-level emergency spillways without downstream energy dissipaters. Many of these spillways have the potential for excessive scour that threatens the safety of the spillway.

A combination of model and prototype experience was used to identify and demonstrate several causes of excessive scour and to identify potential structural solutions. Guidance was developed for evaluating existing high-level emergency spillways from a hydraulic standpoint and for making structural modifications to prevent excessive scour downstream. Energy dissipation within the concrete-lined section of the emergency spillway channel is preferable to dissipation in the natural channel. The Fort Worth District used the guidance for the rehabilitation of Grapeville Spillway, Texas.

Technology products:

Technical Notes HY-FC-1.1, HY-FC-1.2, and HY-FC-1.3
REMR Video Report HY-1

Scour downstream from stilling basins

Numerous older hydraulic structures have experienced excessive scour downstream from the stilling basin or spillway apron. Most of the structures were constructed several decades ago and will be required to operate for several more decades. Without adequate repair or rehabilitation of the area downstream from these structures, they could be undermined.

Methods to repair scour damage downstream from navigation dam stilling basins were investigated for uncontrolled fixed-crest and gated projects. From a review of previous model studies, the causes of scour below the various types and shapes of spillways were identified, and scour protection methods were developed. Additionally, several repair options were developed that include the use of grout-filled fabric bags, use of sunken barges filled with grouted riprap, modification to the spillway apron by adding an end sill, and construction of a secondary stilling basin immediately downstream. A secondary stilling basin will usually result in significant dollar savings over the cost of replacing an inadequate stilling basin.

Corps districts can use this information to design an economical and functional scour protection plan for the remainder of a project's life. A good scour protection design will reduce and possibly eliminate maintenance costs previously required. Some of the repair techniques investigated under this study have been used at Emsworth (Figure 24), Montgomery, and Dashields Dams, Ohio River; at Lock and Dam No. 2, Monongahela River; and at Lock and Dam No. 7, Allegheny River. The use of sunken barges filled with grouted riprap to form a secondary stilling basin at Wilbur Mills Dam resulted in cost savings of $7.1 million.

Figure 24. Grout-filled fabric bags being used to repair a scour area at Emsworth Dam

Technology products:

Technical Notes HY-N-1.1, HY-N-1.3, HY-N-1.5, and HY-N-1.6

Elimination of unfavorable flow conditions near hydraulic structures

Adverse approach flow can accelerate the need for repair, increase the cost of maintenance, and reduce the effective life of a structure. In many cases it is cheaper to modify the approach than to pay the long-term costs that would result from continued operation under existing flow conditions. The modifications, however, must achieve the greatest benefit with the simplest and least expensive remedial measures.

In the past, each modification under consideration was usually tested in the laboratory with a physical model. The expense of model building and testing often limited the number of alternatives that could be explored. A two-dimensional hydrodynamic computer code called STREMR was developed for analysis of approach flows (Figure 25). STREMR can be used as an inexpensive means for screening the efficiency of various structural designs and operations prior to physical model development and testing, thus reducing physical model tests by at least 25 percent. A physical model can then be used for the ultimate testing and refinement of the best option.

Figure 25. The STREMR numerical model can be used to study unfavorable flow conditions at hydraulic structures and develop improved designs

An explicit finite-difference algorithm was developed for numerical modeling of incompressible approach flow near hydraulic structures. It is applicable for transient flow at low Froude number and for steady-state subcritical flow at moderate Froude number. The algorithm has been incorporated in the STREMR computer program, which allows users to simulate the effects of structural modifications and repair measures prior to physical testing.

The STREMR program is widely used by Corps districts, other government agencies, and the private sector. Applications have been made for a pump turbine approach study at Richard B. Russell Reservoir (GA); streambank erosion studies at Grand Pass, Lower Mississippi River and Mud River (WV); spillway approach studies at Prado Dam (CA) and Tenkiller Dam (OK); and a tunnel approach study at Harlan Diversion Tunnels (KY).

Technology products:

Technical Report REMR-HY-5
Technical Notes HY-MM-1.1 and HY-MM-1.2
Computer code STREMR is available from the U.S. Army Engineer Research and Development Center/Hydraulics Laboratory, Vicksburg, MS.

Floating debris control

Floating debris is a continual problem for all users of water bodies. It is destructive to locks, dams, bridges, electric plants, municipal water systems, and even recreational boaters. Wetlands, fish-spawning grounds, and streambanks can be disturbed by floating debris. This research identified and documented methods for collecting, controlling, removing, and disposing of floating debris (Figure 26).

Technology products:

Technical Reports REMR-HY-2 and REMR-HY-3

Repair of navigation training structures

Recent inventories revealed that there are 10,652 Corps training structures located in shallow-draft, nontidal-influenced riverine areas and 554 training structures located in tidally influenced, deep-draft areas. The repair of both estuarine and riverine navigation training structures is a significant maintenance cost within the Corps. The cost includes the repair of stone dikes, pile dikes, and closure structures damaged as a result of normal wear and tear, floating debris, impact from navigation, flood flows, or undermining due to currents.

Figure 26. Trash rake at Chief Joseph Dam, Bridgeport, WA, operated by a gantry crane; it scrapes debris from the trash rack while moving down the rack face

Present repair practices were found to be sufficient for making physical repair to the training structures. However, identification of structures no longer fulfilling their design purpose is also a means to better allocate scarce resources. Refinements to the existing TABS-2 hydrodynamic-sedimentation numerical system helped identify ineffective training structures in the lower Columbia River and the Southwest Pass of the lower Mississippi River (Figure 27). These structures were found to no longer provide the channel maintenance function for which they had been designed and, therefore, could be removed from the annual maintenance cycle. Annual O&M savings of $720,000 were achieved in the Southwest Pass area. The TABS-2 refinements can also be used to help predict which training structures can be expected to have severe erosion problems, thereby achieving timely repair before more costly structure failure occurs.

Figure 27. This training structure on the lower Columbia River was one of those identified as no longer needed

Technology products:

Technical Reports REMR-HY-1, REMR-HY-6, REMR-HY-8
Unnumbered Report, "Proceedings of REMR Workshop on Repair and Maintenance of Shallow-Draft Training Structures" (February 1987)

Evaluation of training structures

The maintenance of inefficient training structures provides a significant drain on O&M funds. The existing TABS system of numerical models had been proven useful in the evaluation and design of training structures in numerous studies. Improvements were made to the models to allow for quickly and easily setting up problems and analyzing them on in-house micro- and minicomputers. A graphics package was also added to the system. Since the software can be used by Corps FOAs (field operating activities) with little if any assistance from the laboratories, more training structures are being evaluated throughout the Corps to screen the performance of existing structures and eliminate the maintenance of inefficient structures. A few early examples for which the improved models were used include the Houston Ship Channel Design (TX), San Francisco Bay Channel Design (CA), Columbia River Channel Design (OR), Everglades National Park Flood Study (FL), New York Harbor (NY), and Upper Mississippi River Locks and Dams.

This modeling work was the basic building block for three complete modeling systems: Surface Water Modeling System (SMS), Watershed Modeling System (WMS), and Groundwater Modeling System (GMS). These systems have significantly improved the efficiency of modeling studies to the point where a study can be completed more quickly and for about one quarter the cost. Cost savings from the use of these systems are well over $1 million per year, merely from the reduced costs of conducting the studies. There are additional benefits resulting from each site-specific study.

Guidelines were also developed for lateral dike spacing in estuaries. The guidelines were based on laboratory flume analyses and apply to dikes designed for channel maintenance.

Technology products:

Technical Report REMR-HY-9
Technical Notes HY-N-1.2 and HY-N-1.8
Computer models of the SMS, WMS, and GMS systems can be obtained from the U.S. Army Engineer Research and Development Center/ Hydraulics Laboratory, Vicksburg, MS.

Evaluation and maintenance of high-velocity channels

The hydraulic performance of a high-velocity channel depends on maintaining a supercritical flow regime over specified portions of its length. Predicting the potential location of shocks, such as oblique standing waves and hydraulic jumps, and determining the super-elevation of the water surface in channel bends are necessary to evaluate and maintain the required wall heights.

A numerical flow model, HIVEL2D, has been developed as a tool to evaluate high-velocity channels (man-made concrete-lined channels with hydraulically steep slopes). The successful design of high-velocity channels depends on accurate prediction of the flow depths. HIVEL2D is a depth-averaged, two-dimensional flow model designed specifically for flow fields that contain supercritical and subcritical regimes as well as the transitions between the regimes.

The model was first used for a study of the San Timoteo Creek Flood-Control Channel, California. A physical model study (Figure 28) would have cost $350,000. Use of the HIVEL2D model resulted in savings of $300,000. The model has been transferred to Corps FOAs, where it is used to conduct studies with little or no assistance from laboratory personnel.

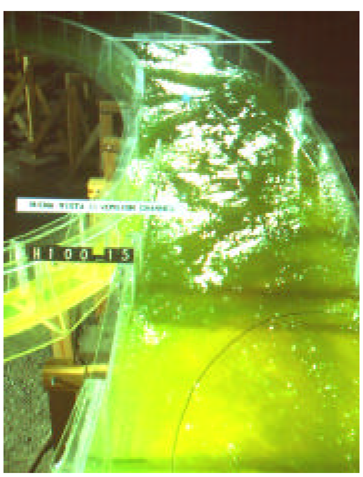

Figure 28. Physical model test such as this are expensive. Numerical models such HIVEL2D can be used to reduce the number of physical model tests required to develop a satisfactory design

Technology products:

Technical Reports REMR-HY-12 and REMR-HY-13
Computer code HIVEL2D can be obtained from the U.S. Army Engineer Research and Development Center/Hydraulics Laboratory, Vicksburg, MS.

Icing of machinery components at Corps structures

Icing of machinery such as dam gates, lock gates, and seals is a problem at Corps projects during cold weather. A survey was conducted of Corps divisions and districts to obtain information on icing problems and existing solutions.

Twelve serious ice problems at locks were identified, the most severe being ice accumulation in the miter gate recess. Fifteen ice problems around dams were identified, the most severe being ice accumulation upstream of a dam.

The most common method of dealing with ice problems has previously been chipping off the ice, a labor-intensive, time-consuming, and hazardous practice. Other more efficient and more effective methods, such as air-bubbler systems and panel heaters, were studied. The rationale was to prevent ice from forming or, if this is not possible, to provide efficient, economical solutions. Guidance was developed on the use of bubbler systems, panel heaters, radiant heaters, side-seal heaters, J-seal heaters, and others.

Technology products:

Technical Reports REMR-HY-10 and REMR-HY-14
Technical Notes HY-N-1.9, HY-N-1.10, and HY-N-1.11

Lock accident study

A survey of lock accidents was conducted that included locks on the Upper Mississippi and Ohio Rivers and their navigable tributaries such as the Tennessee River.

In order to design elements such as miter gates to withstand minor impacts, the engineer must know the total energy expected to be produced by a vessel impacting these structures. In addition to the simple kinetic energy produced by a vessel's movement as related to its mass and speed, a number of complicated hydrodynamic forces (including drag and wave propagation) can affect the total energy of the moving vessel. This is especially evident as the vessel enters or travels through geometrically restrictive areas, such as lock chambers. A 1:25-scale physical model and remote-operated towboat and push barges were used to measure impact parameters.

Technology products:

Technical Reports REMR-HY-7 and REMR-HY-4
Technical Note HY-N-1.7

Coastal

Evaluation, repair, and rehabilitation techniques for coastal structures such as jetties and breakwaters were investigated under the coastal problem area.

Sealing of permeable breakwaters and jetties

Rubble-mound breakwaters and jetties are intended to protect harbors and navigation channels from excessive wave energy and to prevent shoaling of channels and boat-mooring areas by littoral material. The cores of many such Corps coastal structures have deteriorated and become permeable to such an extent that they do not serve, or only partially serve, their original intended function.

A cost-effective alternative to traditional methods of rubble-mound structure sealing (that is, dismantling to rebuild core sections, chinking layers along surfaces, additional armoring layers, etc.) was determined to be drilling and grouting (sealing) a vertical barrier curtain along the center line of the structure.

Sealing permeable breakwaters or jetties (Figure 29) should be approached from the standpoint of preventing wave or sand movement through the structure and not from the requirement of imparting structural stability or strength. In planning a sealing operation, a quantitative determination must be made of the wave energy or sand passing through the structure to ascertain economic benefits.

Figure 29. The south jetty at Port Everglades, FL, was sealed using a drilling and grouting technique

Technology products:

Technical Reports REMR-C0-8, REMR-CO-13, REMR-CO-15, and REMR-CO-16
Technical Notes CO-RR-1.2 and CO-RR-8.1

Reducing wave runup and overtopping

Problems associated with runup and overtopping have occurred on about 20 percent of the Corps' coastal structures. The range of problems from runup and overtopping includes the following: excessive wave action on the lee side of breakwaters and jetties; flooding and erosion on the back side of seawalls, sea dikes, and bulkheads; and backside subsidence, erosion and, sometimes, collapse of revetments.

Mathematical models and flume studies were used to evaluate and rank the hydraulic performance of a number of seawall/revetment configurations. For existing revetments, it was found that an attached low berm fronting a rubble revetment significantly decreases wave runup and overtopping. This technology was used at the Temple Emanuel project on the Chicago waterfront (Figure 30) and resulted in savings of 12 percent over the costs of the traditional high-berm revetment.

Figure 30. Low-berm revetment installed at Temple Emanuel to decrease wave runup and overtopping

Technology products:

Technical Reports REMR-CO-7 and REMR-CO-17
Technical Notes CO-RR-1.3, CO-RR-1.4, and CO-RR-1.5

Rehabilitation of rubble-mound structure toes

Many breakwater failures have been attributed to failure of the toes of these structures. Previously, no firm guidance existed to aid Corps personnel in designing toe berms, and most design work was carried out using limited local field experience related to past successes and failures.

A series of two- and three-dimensional breakwater stability physical model experiments was developed and conducted to address the sizing of toe berm and toe buttressing stone in breaking wave environments. The two-dimensional tests focused on sizing of toe stone on rubble-mound structure trunks exposed to 90-deg wave attack, that is, wave orthogonals perpendicular to structure crest. Toe berm armor stone sizing for oblique wave attack on rubble-mound structure heads and trunks was examined in the three-dimensional model tests. Guidance for sizing toe berm armor stone was developed for a range of wave and still-water level conditions. Guidance for sizing of toe buttressing stone was addressed for a limited set of incident wave conditions on structure trunks. Use of this new guidance should eliminate wave-induced toe berm failures and result in significant dollar savings for the Corps.

Technology products:

Technical Reports REMR-CO-1 and REMR-CO-12

Evaluation of damage to underwater portions of coastal structures

The effectiveness of techniques for inspection and evaluation of underwater damage is limited by the severe conditions encountered in the zone surrounding coastal structures, including wave energy, strong currents, and low underwater visibility. Current technology and methods for performing inspections were examined, including diver and crane surveys, underwater video, and commercially available side-scan and other sonars. (See Subject Area section Imaging and inspection of underwater portions of coastal structures.) Training was provided to Corps personnel, and the guidance was used in evaluating the underwater parts of the Humboldt and Crescent City jetties on the California coast.

Technology products:

Technical Reports REMR-CO-11 and REMR-CO-19
Technical Notes CO-SE-1.1, CO-SE-1.2, CO-SE-1.3 and CO-SE-1.4

Use of dissimilar armor for repair and rehabilitation

Model tests have shown that overlays of concrete units such as dolosse (Figure 31) and tribars over stone require larger sizes than if the structure were originally designed for those particular units. Thus, the design guidance for new structures is inappropriate for use in the design of repairs and rehabilitations involving dissimilar armor.

Figure 31. Dolos units being used to repair Cresent City Breakwater

Stability tests were conducted of dolos overlays of stone-armored, dolos-armored, and tribar-armored breakwater and jetty trunks subjected to breaking waves. Tests were also conducted of tribar overlays of stone-armored breakwater and jetty trunks and dolos overlays of stone-armored breakwater heads subjected to breaking waves. The results from these tests can be used to design appropriately sized armor units for repair and rehabilitation of breakwaters and jetties.

Technology products:

Technical Reports REMR-CO-2, REMR-CO-4, REMR-CO-5, REMR-CO-6, REMR-CO-9, and REMR-CO-14

Toe stability in a combined wave and flow environment

The design and construction of a stable structure toe is an important part of a repair or rehabilitation program for a rubble-mound structure. Previous guidance was developed for stable rubble-mound structure toes placed in a breaking wave environment. (See Subject Area section Rehabilitation of rubble-mound structure toes.) Additional research was conducted to evaluate the stability of toe stone repair armor when placed in a combined wave and flow environment.

A method to determine toe stone size was developed based on fixed-bed model experiments using varying values of wave height, wave period, ebb flow velocity, toe stone size, and water depth. The resulting recommendation is that, considering both wave and flow conditions, the toe weight required may be greater than one tenth the primary armor weight presently recommended for acceptable wave stability.

The movable-bed model experiments indicated that toe stone size selected using this method was stable for combined wave and current conditions. Results also indicated that toe protection should cover at least half the scour hole width.

Technology products:

Technical Report REMR-CO-20

CORE-LOCÔ concrete armor units

No comprehensive design guidance previously existed for concrete armor units used in the repair and rehabilitation of coastal structures. For this reason, and because of the very complex nature of coastal structure environments, concrete armor design was either overly conservative, yielding high initial costs, or nonconservative, yielding high rehabilitation costs.

A survey was conducted to document the performance of concrete armor units, to verify and expand armor design guidance, and to refine guidance on concrete armor construction practices. A new type of concrete armor unit called CORE-LOC™ (Core-Loc) was developed and patented worldwide (Figure 32). This unit provides superior structural and stability characteristics and good interlocking with dolos armor units. Guidance on the construction of Core-Loc units and their use for repair was developed. Core-Loc units have been used for repairs at Ventura breakwater, California, and Manasquan jetties, New Jersey. The units are also planned for the rehabilitation of Kaumalapau Breakwater, Hawaii, where their use will result in estimated savings of $4.6 million over other alternatives. In addition to initial cost savings, the units provide a more competent design that results in less breakage and thus lower maintenance and repair cost in the future.

An aesthetically pleasing uniformly placed concrete armor unit called Vatia Stone was also developed and patented.

Figure 32. CORE-LOC units were used for the repair of Venture Breakwater, California

Technology products:

Technical Report REMR-CO-18
Miscellaneous Paper CHL-97-6
Technical Notes CO-RA-1.2, C0-RA-1.1, CO-RR-1.6, and CO-RR-1.7

Imaging and inspection of underwater portions of coastal structures

Most damage to coastal structures, especially rubble-mound breakwaters and jetties, occurs to the underwater portion of the structure. Underwater damage (such as scour, settlement, and scattering and breakage of armor units) is not often exhibited on the surface, and damage can progress until a major structural collapse occurs. The capabilities of commercially available multibeam systems, such as the SeaBat 9001 multibeam sonar system, offer great promise in meeting the needs for inspecting underwater portions of coastal structures.

Field demonstrations and trials were conducted with the SeaBat 9001 system. The SeaBat system (Figure 33) was successful in providing accurate, high-resolution hydrographic data on the underwater condition of various structures. The system provided the first detailed picture of the underwater configuration of the Yaquina Bay north jetty. With multibeam sonar systems, it is now possible to have types of survey information that were previously impractical to obtain or were unattainable, leading to safer, more cost-effective management of coastal structures over their lifetimes.

Figure 33. Survey boat equipped with Seabat sonar system

Technology products:

Technical Report REMR-CO-19
Technical Note: CO-SE-1.5

Case histories of Corps breakwater and jetty structures

A series of case histories of Corps of Engineers breakwater and jetty structures were developed. These case histories serve two important purposes: to lend insight into the scope, magnitude, and history of coastal breakwaters and jetties under Corps jurisdiction (including their maintenance and repair history and their methods of construction) and to make this information available to Corps personnel. Case histories were prepared for the South Pacific, South Atlantic, North Central, Pacific Ocean, North Atlantic, North Pacific, Lower Mississippi Valley, Southwestern, and New England divisions.

Technology products:

Technical Reports REMR-CO-3, Reports 1 through 9
Technical Note CO-RA-1.1

Electrical and Mechanical

Maintenance techniques and replacement materials and procedures for the electrical and mechanical components of Corps projects were studied under this problem area.

Control of roosting birds and bird waste

Management strategies for bird-pest populations that cause extensive economic losses or represent serious threats to human health or safety have been well researched. However, small-scale or local bird nuisance or damage problems had not been as thoroughly addressed, particularly in controlled experiments.

The methodologies to control or manage most bird pests (Figure 34) are relatively well known and, to varying degrees, they are species and site specific. Nevertheless, there must usually be some fine-tuning by experienced and perceptive pest managers to effectively solve a specific problem or problems. An integral part of any pest management program is the assessment and monitoring of potential environmental hazards.

A comprehensive REMR report on this subject is available that includes information on the types of damage caused by various pest species, human health hazards, general bird management strategies, and specific species recommendations. The report is an excellent source of bird control information and is being used by the Animal Damage Control Section of the U.S. Department of Agriculture, Army installations, Naval bases, and private consultants, as well as by Corps field offices.

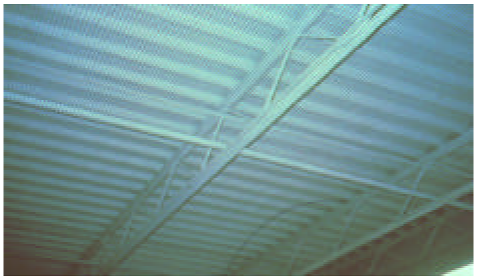

Figure 34. Wire mesh installed on the underside of open-air structures can be used to prevent birds from roosting on the structure

Technology products:

Technical Reports REMR-EM-2
Unnumbered Report, "Proceedings of REMR Workshop on Management of Bird Pests" (Apr 1988) [also published as Technical Report N-90/03, Dec 1989, U.S. Army Construction Engineering Research Laboratory]

Evaluation of hydroelectric generators

Increasing numbers of hydroelectric units are going to need rewinding because of advancing age and problems with thermosetting insulation systems. There was a need for guidance to help Corps field offices determine when to rewind generators.

Electrical tests and test equipment, when used along with thorough visual inspections in a regular insulation-maintenance program, can extend insulation life and reduce unscheduled outages, thus reducing the possibility of major equipment damage and loss of revenue from the sale of power. A routine inspection and testing program can find minor problems that can be corrected before they become major. A regular inspection and testing program can indicate the present condition of the insulation and can reveal the need for special tests and long-term trends.

Industry-accepted visual inspections and electrical tests were documented, guidance was developed for determining when a generator should be rewound, and a recommended program for periodic routine inspections and testing was developed.

Technology products:

Technical Report REMR-EM-4

Underwater applied coatings

Eleven proprietary protective coatings of differing composition, all formulated for application to damp or immersed surfaces, were tested to determine their applicability for underwater maintenance painting (Figure 35). The putty-like splash-zone compounds developed in the 1960s were easy to apply, but the application was slow and expensive. The materials formed thick protective coatings, but could not be used in water below 16 °C (60 °F).

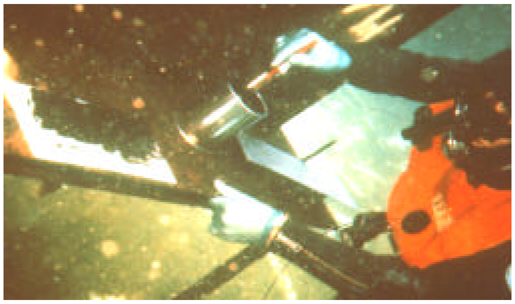

Figure 35. An underwater coating being applied to a test panel

The products formulated for underwater application by brush or roller were generally more difficult to apply than indicated in the suppliers' advertisements. However, once applied, they formed tightly adhering protective films to properly prepared surfaces. Abrasive blasting was found to be the best method for underwater surface preparation.

While these underwater coatings are not capable of the level of protection provided by coatings applied above water, they can be used to increase the service life of corrosion-prone structures when dewatering is impractical.

Technology products:

Technical Report REMR-EM-3
Technical Note: EM-PC-1.3

High-solids coatings

Air pollution regulations are becoming increasingly restrictive of the amount of volatile organic compounds in paint systems. The vinyl paints the Corps uses contain high percentages of these compounds, which will likely prohibit their use in the future. High-solids coatings contain fewer volatile organic compounds and are attractive environmentally.

It was generally recognized that technology was not available to produce high-solids coatings that could withstand high-velocity, abrasive waters. Therefore, a study was conducted to identify and evaluate durable high-solids coatings for use on hydraulic structures exposed to immersion in low-velocity, nonabrasive waters.

Twenty-four coatings were tested in the laboratory, and four of these were selected for field application to the downstream waterline area of a tainter gate at New Boston, IL (Figure 36). The high-solids epoxies were judged easily applied by painting contractors with average experience. They can be applied for about one half the cost of standard vinyl coating systems and should perform well when used in low-abrasive environments.

Technology products:

Technical Reports REMR-EM-7 and REMR-EM-10
Technical Note EM-PC-1.4

Figure 36. Application of high-solids epoxy system to a test section on a tainter gate at Dam No. 17, Mississippi River

Use of ceramic anodes to prevent corrosion

Silicon-iron and graphite anodes that have been used for the past 30 years are brittle, cannot be machined or welded, and have very high consumption rates. As a result, large anodes have been required, and their size has made them vulnerable to debris or ice damage, and prone to field installation problems.

In response to these problems, a new type of anode based on a conductive ceramic was developed (Figure 37). This new anode is proving to be a major technological breakthrough in corrosion prevention, since the consumption rate of conducting ceramic materials (such as ferrites) is 200 times lower than that of silicon-iron and graphite anodes. The advantage of this is the ability to use smaller anodes, thus minimizing their exposure to impact damage and allowing placement in areas where larger anodes cannot be installed. Other advantages of ceramic anodes include their ability to be installed by nonspecialized workers, their life-cycle cost (about half that of other cathodic protection systems), their reliability (nearly double that of the other systems), and the fact that they can be installed underwater.

Technology products:

Technical Notes EM-CR-1.2, EM-CR-1.3, EM-PC-1.1

Figure 37. Ceramic anodes installed on a lock gate

Stainless steels for locks, dams, and hydroelectric plant applications

Carbon steels and low-alloy steels have been the primary materials used to construct locks, dams, and hydroelectric plants. To a much lesser extent, components for these facilities were fabricated from 400-series martensitic stainless steels and 300-series austenitic stainless steels.

After a thorough investigation into the mechanical properties, corrosion resistance, and cost of eight wrought stainless steels, it was concluded that no single stainless steel can offer optimum performance under all conditions and that selection of the steel must consider all factors. General guidelines were developed regarding the use of stainless steels for locks, dams, and hydroelectric plant applications.

Technology products:

Technical Report REMR-EM-6
Technical Notes EM-CR-1.1, EM-CR-1.5, EM-CR-1.6 and EM-CR-8.1

VOC-compliant coating system

The Corps of Engineers has used solution vinyl paints for the corrosion protection of hydraulic structures on inland waterways for many years. These coatings have an excellent service life; however, the liquid paint contains high quantities of solvents. To comply both with existing and anticipated pollution regulations, it was necessary to evaluate potential coatings for replacing those currently used.

Ten elastomeric polyurethanes were tested in the laboratory; six were recommended for field tests. The extreme abrasion and impact environment that existed at the field test site resulted in early failures of the paint systems. Failures occurred at the polyurethane-epoxy bond coat interface. Until stronger adhesion can be effected between the polyurethane and the bond coat, these systems will remain ineffective in high-abrasion areas such as tainter gates.

Technology products:

Technical Report REMR-EM-9

Lead-pigmented paints on hydraulic structures

Because of the environmental problems leaded paint can create, regulations have been enacted to help protect the environment and the safety and health of workers. However, these regulations have had a significant impact on the cost of painting, on painting with leaded paints, and on the removal of these paints. New methods have been developed to deal with the removal of leaded paints, and the costs of these methods vary, sometimes considerably, with the structure involved and the removal method used.

Guidance was developed for removal of leaded paint from hydraulic structures, and for maintenance painting methods that extend the service life of leaded paint coatings (Figure 38). Estimated cost avoidance of $2.5 million over 5 years was realized by improved maintenance practices.

Figure 38. Many Corps structures contain metal components that have been coated with lead-based paints

Technology products:

Technical Report REMR-EM-8
Technical Note: EM-PC-1.5

Paint systems for damp surfaces

Numerous steel structures inside locks and dams are subjected to conditions of constant condensation (Figure 39). The surfaces of these structures normally can be blast-cleaned to a white metal grade, but condensation and/or water leaking around seals immediately make the surfaces too wet for the application of many coatings. The coatings industry has recently developed and marketed new coatings that adhere to wet or damp steel. A number of these products were evaluated, both in the laboratory and on structures in the field. Results indicate that some of these coatings hold promise for long-term corrosion protection. Based on the results, a draft Commercial Item Description was developed to specify durable coatings for wet and damp steel surfaces.

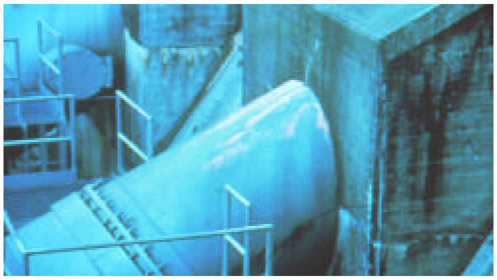

Figure 39. Condensation on metal components of dams can sometimes require the use of paint systems designed for damp surfaces

Lubricants for hydraulic structures

Uniform guidance regarding the specification and use of lubricants for hydraulic structures was not previously available. An investigation was conducted to determine the lubrication practices and problems by surveying all Corps installations having hydraulic structures. Equipment manufacturers and lubricant producers were contacted to obtain state-of-the-art information to help installations determine and obtain appropriate lubricants.

Environmentally compatible lubricants were identified, and their use at Corps projects is being investigated under the High-Performance Materials and Systems Research Program (http://www.wes.army.mil/SL/HPMS/hpms.htm).

Technology products:

Technical Report REMR-EM-5
Technical Note: EM-MM-1.1

Environmental Impacts

A significant part of the effort under this program area was to evaluate the potential impact on the environment of the materials and techniques investigated under the other problem areas. An environmental review was conducted of all the technology produced under the Phase I effort, and mitigating and remedial alternatives were recommended when necessary.

In addition, several documents were produced to assist field personnel in the environmental assessment of maintenance, repair, and rehabilitation efforts at Corps projects. Guidance was developed for compliance with environmental laws while conducting REMR activities.

Effects of vegetation on the structural integrity of levees

Corps guidelines for levee maintenance and operation limited vegetation on the embankment to sod-forming grasses of 5- to 30-cm (2- to 12-in.) heights to provide for structural integrity, inspectability, and unhindered flood-fighting access to levees. However, this level of maintenance is costly and often detrimental to the quality of riparian habitat. Environmental issues encountered range from habitat cover to violation of the Endangered Species Act.

A study was conducted to investigate the relationship between vegetation (woody plant species) and the structural integrity of river levees (Figure 40). The study found that, for sandy overbuilt levees, plant roots reinforce the levee soil and increase shear strength in a measurable manner.

Figure 40. Levee containing woody vegetation

Technology products:

Technical Report REMR-EI-5
Technical Notes EI-M-1.3 and EI-M-1.4

Applicability of environmental laws to REMR activities

The commitment to protect, conserve, and enhance the environment has been expressed in numerous far-reaching laws, statutes, and regulations. These environmental laws apply to private and government agency planning, construction, and operations and maintenance (O&M) activities. The environmental laws and regulations were examined to determine their applicability to REMR activities. The purpose of each law was explained, and the types of REMR activities that could be covered by the law were identified.

Compliance actions required under the environmental laws were summarized. Information was developed on compliance documentation required and sources of assistance/advice.

Technology products:

Technical Reports REMR-EI-1 and REMR-EI-3
Technical Note EI-M-1.1 and EI-M-1.2

Seasonal regulation of REMR activities

Some activities associated with REMR have the potential to affect environmental quality in adjacent aquatic and/or terrestrial habitats. As a consequence, these activities may affect sensitive organisms in the vicinity of the structure. Because the presence and abundance of organisms in these habitats fluctuate seasonally, seasonal regulation of REMR activities at a structure may be justified to protect a given biological resource.

A general evaluation procedure was developed which Corps personnel can use to determine whether concerns about sensitive biological resources are justified. In general, potential impacts of REMR activities associated with particular types of structures are largely a function of the material makeup of the given structure and preparatory activities at the site.

Technology products:

Technical Report REMR-EI-4
Technical Note: EI-R-1.1

Operations Management

A computer-aided system (the REMR Management System) for managing REMR activities for civil works structures was developed. The system consists of three modules: Basic Functions module, Condition Evaluation and Rating module, and Consequence Modeling module. The Basic Functions module contains the procedures for data management and life-cycle cost analysis. The Condition Evaluation and Rating module contains a collection of condition evaluation procedures for various types of structures. The Consequence Modeling module includes tools useful for long-term planning.

The REMR Management System is designed as a planning tool and an information system for project-level management (Figure 41). It provides procedures for condition inspection and evaluation, data management, and economic analysis.

These procedures can be used to prioritize REMR activities based on condition (Figure 42), to select maintenance and repair alternatives based on performance, and to compare the cost of various alternatives based on life-cycle costs. The REMR Management System promotes faster and more objective, condition-oriented performance of REMR activities and can be used to ensure that scarce maintenance and repair funds are spent on the projects in most need.

Condition evaluation and rating systems were developed for 14 types of structures. All systems use the same rating scale. A rating of 70 to 100 indicates that no immediate action is required for the structure to function properly. A rating of 40 to 69 requires an economic analysis of repair alternatives to determine appropriate maintenance actions. A rating of 0 to 39 requires a detailed evaluation of the structure to determine the type of repair, rehabilitation, or reconstruction required.

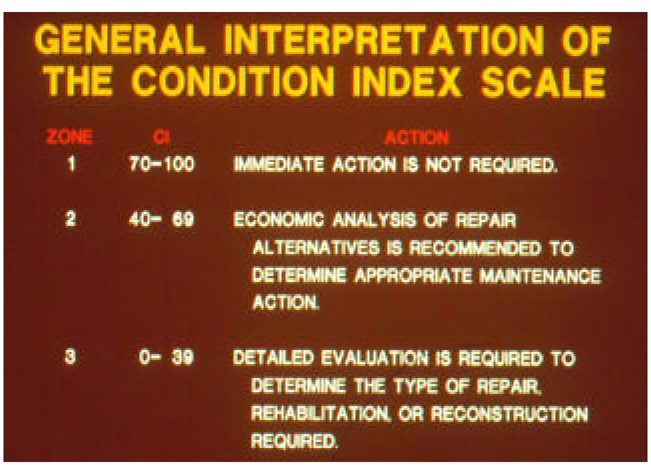

Figure 41. REMR Management System, Condition Index Scale

Figure 42. Inspection of a concrete lock wall for defects

Management systems were developed for the following structures:

Timber dikes	Technical Report REMR-OM-5; Technical Note OM-MS-1.6
Steel sheet pile structures	Technical Reports REMR-OM-3 and -OM-9 Technical Note OM-MS-1.4
Lock miter gates	Technical Reports REMR-OM-7, -OM-8, and Supplement Technical Note OM-MS-1.3
Concrete lock walls	Technical Reports REMR-OM-4, -OM-10, and -OM-12 Technical Note OM-MS-1.2
Sector lock gate	Technical Report REMR-OM-13 Technical Note OM-MS-1.7
Lock filling and emptying valves	Technical Report: REMR-OM-14 Technical Note: OM-MS-1.8
Tainter and butterfly valves	Technical Report REMR-OM-14 Technical Note OM-MS-1.11
Lock and dam tainter gate	Technical Report REMR-OM-17 Technical Note OM-MS-1.14
Concrete gravity dams, retaining walls, and spillways	Technical Reports REMR-OM-16 and REMR-OM-22 Technical Note OM-MS-1.10
Stone training dikes and revetments	Technical Reports REMR-OM-21 and REMR-OM-23 Technical Note OM-MS-1.9
Roller gates	Technical Report REMR-OM-18 Technical Note OM-MS-1.13
Earth and rock dams	Technical Report REMR-OM-25
Lock and dam operating equipment	Technical Report REMR-OM-19 Technical Note OM-MS-1.12
Rubble breakwaters and jetties	Technical Reports REMR-OM-11, -OM-20, and -OM-24 Technical Note OM-MS-1.5

Training and software programs for the above systems are available from the U.S. Army Engineer Research and Development Center/Construction Engineering Research Laboratory, Champaign, IL.

3 Overview of Program Benefits

Technology Transfer

There is no single most successful method of transferring technology. What works well for one type of technology and one type of user may not be the best choice for others. Therefore, a successful technology transfer effort for a large research program must use a combination of methods.

Methods used to transfer REMR technology included the following: technical reports, workshops, training courses, video reports, field demonstrations, an electronic bulletin board (proved ineffective and was terminated), computer databases, briefings, articles in technical journals, input to engineer manuals, Executive Notes, an Information Exchange Bulletin, *The REMR Notebook*, and a program homepage on the Internet.

The information exchange bulletin was appropriately named *The REMR Bulletin*. Unlike some newsletters and bulletins that concentrate on current and upcoming events and, thus, quickly become outdated, *The REMR Bulletin* presented technical articles on maintenance and repair procedures and materials. Each article included the name and telephone number of a person to contact for additional information. Later issues of *The REMR Bulletin* (1995-98) are available on the Internet.

The REMR Notebook was used to publish fact sheets on materials, techniques, and equipment. Early in the REMR Research Program, the need surfaced to make REMR technology readily available to users. With the number of studies being conducted and the number of reports being generated, it was necessary to present the technology in a concise form. *The REMR Notebook* was developed for that purpose. The idea was to present a particular technology without all the background data normally included in a technical report. The technical notes, limited to a few pages, provided the basic information, and included references and a point of contact for additional information. The notebook was very effective for the immediate transfer of REMR technology and was originally published in 3-in. loose-leaf binders. Later in the program the notebook was published electronically and made available on the Internet.

During Phase II of the REMR Research Program, maximum use was made of the growing awareness and use of the Internet for the rapid transfer of REMR technology. A REMR homepage (http://www.wes.army.mil/REMR/remr.html) was established and expanded through the end of the program. The Web site now includes *The REMR Notebook*, the last 10 issues of *The REMR Bulletin*, a listing of REMR Technical Reports, and an Annotated Bibliography.

Conclusion

The Corps was one of the first Federal agencies to recognize the need for research to address the nation's deteriorating infrastructure. The Repair, Evaluation, Maintenance, and Rehabilitation Research Program was implemented to address that need and has clearly demonstrated the benefits of research in getting more value for the dollars spent on maintenance and repair activities. After its fifth year, the REMR Program was credited with dollar savings that exceeded the full 6-year cost of the Phase I effort, and by the end of the sixth year was credited with savings of more than $68 million. These figures were based on first-time uses of only a portion of the total technology produced.

Savings from the use of REMR technology 5 years after the completion of the Phase I effort exceeded $200 million for the Corps alone. Additional savings and benefits accrue each time the technology is applied. Savings from use of REMR technology produced by the Phase II effort are expected to be similar to those experienced from the Phase I effort, with a minimum return on investment of 6 to 1.

In addition to dollar savings, the program has resulted in other benefits, such as improved safety and reliability, reduced manpower requirements, and improved operational capabilities. The technology that resulted from this research program is expected to continue to provide benefits to the Corps, other government agencies, and private industry.

Appendix A
Listing of REMR Reports

Coastal Applications

REMR-CO-1
"Stability of Rubble-Mound Breakwater and Jetty Toes; Survey of Field Experience," by Dennis G. Markle [AD-A180 108][1]

REMR-CO-2
"Prototype Experience with the Use of Dissimilar Armor for Repair and Rehabilitation of Rubble-Mound Coastal Structures," by Robert D. Carver [AD-A204 081]

REMR-CO-3, "Case Histories of Corps Breakwater and Jetty Structures"

Report 1, "South Pacific Division," by Robert R. Bottin, Jr. [AD-A192 294]

Report 2, "South Atlantic Division," by Francis E. Sargent [AD-A200 458]

Report 3, "North Central Division," by Robert R. Bottin, Jr. [AD-A198 436]

Report 4, "Pacific Ocean Division," by Francis E. Sargent, Dennis G. Markle, and Peter J. Grace [AD-A199 879]

Report 5, "North Atlantic Division," by Ernest R. Smith [AD-A207 146]

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[1] A very limited number of copies of REMR reports are available for Corps of Engineers Divisions and Districts and other Government agencies. Requests should be directed to the ERDC-Vicksburg (e-mail *ruffj@wes.army.mil*, 601-634-2587, fax 601-634-2873). The general public can purchase copies of REMR reports through the U.S. Department of Commerce's National Technical Information Service (NTIS) (*http://www.ntis.gov/*). When ordering from NTIS, include the AD-A number [shown in brackets for each report listed] as well as the report title and author(s). Military customers can obtain Government documents at a lower cost through the Defense Technical Information Center (DTIC) (*http://www.dtic.mil/)*. Electronic full text (in PDF format) is available on-line for most REMR reports completed since 1998. Footnotes on the succeeding pages provide information on accessing these reports via the Internet.

Report 6, "North Pacific Division," by Donald L. Ward [AD-A203 865]

Report 7, "New England Division," by Francis E. Sargent and Robert R. Bottin, Jr. [AD-A204 082]

Report 8, "Lower Mississippi Valley Division," by Francis E. Sargent and Robert R. Bottin, Jr. [AD-A204 083]

Report 9, "Southwestern Division," by Francis E. Sargent and Robert R. Bottin, Jr. [AD-A204 084]

REMR-CO-4
"Stability of Dolos and Tribar Overlays for Rehabilitation of Stone-Armored Rubble-Mound Breakwater and Jetty Trunks Subjected to Breaking Waves," by Robert D. Carver and Brenda J. Wright [AD-A192 487]

REMR-CO-5
"Stability of Dolos Overlays for Rehabilitation of Dolos-Armored Rubble-Mound Breakwater and Jetty Trunks Subjected to Breaking Waves," by Robert D. Carver and Brenda J. Wright [AD-A195 392]

REMR-CO-6
"Stability of Dolos Overlays for Rehabilitation of Tribar-Armored Rubble-Mound Breakwater and Jetty Trunks Subjected to Breaking Waves," by Robert D. Carver and Brenda J. Wright [AD-A198 877]

REMR-CO-7
"Methods to Reduce Wave Runup and Overtopping of Existing Structures," by John P. Ahrens [AD-A200 455]

REMR-CO-8
"State-of-the-Art Procedures for Sealing Coastal Structures with Grouts and Concretes," by David P. Simpson [AD-A208 884]

REMR-CO-9
"Stability of Dolos Overlays for Rehabilitation of Stone-Armored Rubble-Mound Breakwater Heads Subjected to Breaking Waves," by Robert D. Carver [AD-A208 577]

REMR-CO-10
"Study of Breakwaters Constructed with One Layer of Armor Stone, Detroit District," by John R. Wolf [AD-A212 631]

REMR-CO-11
"Underwater Inspection of Coastal Structures Using Commercially Available Sonars," by William M. Kucharsky and James E. Clausner [AD-A224 169]

REMR-CO-12
"Stability of Toe Berm Armor Stone and Toe Buttressing Stone on Rubble-Mound Breakwaters and Jetties; Physical Model Investigation," by Dennis G. Markle [AD-A213 589]

REMR-CO-13
"Laboratory Techniques for Evaluating Effectiveness of Sealing Voids in Rubble-Mound Breakwaters and Jetties with Grouts and Concretes," by David P. Simpson and Jeffery L. Thomas [AD-A220 178]

REMR-CO-14
"Repair of Localized Armor Stone Damage on Rubble-Mound Structures; Coastal Model Investigation," by Donald L. Ward and Dennis G. Markle [AD-A227 014]

REMR-CO-15
"Field Evaluation of Port Everglades, Florida, Rehabilitation of South Jetty by Void Sealing," by Julie Dean Rosati and Thomas A. Denes [AD-A229 176]

REMR-CO-16
"Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing: Summary Report," by David P. Simpson, Julie D. Rosati, Lyndell Z. Hales, Thomas A. Denes, and Jeffrey L. Thomas [AD-A229 927]

REMR-CO-17
"Use of a Rubble Berm for Reducing Runup, Overtopping, and Damage on a 1V to 2H Riprap Slope," by Donald L. Ward and John P. Ahrens [AD-A266 377]

REMR-CO-18
"Preliminary 3-D Testing of CORE-LOC™ as a Repair Concrete Armor Unit for Dolos-Armored Breakwater Slopes," by George F. Turk and Jeffrey A. Melby [AD-A331 917]

REMR-CO-19
"Coastal Structure Inspection Technologies; Investigation of Multibeam Sonars for Coastal Structure Surveys," by Terri Prickett

REMR-CO-20[1]
"Toe Stability of Rubble-Mound Structures in a Breaking Wave and Ebb Flow Environment," by Ernest R. Smith [AD-A369 056]

Concrete and Steel Structures

REMR-CS-1
"Engineering Condition Survey of Concrete in Service," by Richard L. Stowe, and Henry T. Thornton, Jr. [AD-A148 893]

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[1] Full text available on-line (in PDF format) at *http://www.dtic.mil/stinet/index.html*.

REMR-CS-2
"The Condition of Corps of Engineers Civil Works Concrete Structures," by James E. McDonald and Roy L. Campbell, Sr. [AD-A157 992]

REMR-CS-3
"Latex Admixtures for Portland Cement Concrete and Mortar," by Dennis L. Bean and Tony B. Husbands [AD-A171 352]

REMR-CS-4
"Repair of Waterstop Failures: Case Histories," by James E. McDonald [AD-A176 937]

REMR-CS-5
"Instrumentation Automation for Concrete Structures"

Report 1, "Instrumentation Automation Techniques," by John Lindsey, David Edwards, Aubrey Keeter, Tom Payne, and Roger Malloy [AD-A178 139]

Report 2, "Automation Hardware and Retrofitting Techniques," by Aubrey Keeter, Byron Stonecypher, Tom Payne, Mathew Skerl, Jim Burton, and James Jennings [AD-A192 753]

Report 3, "Available Data Collection and Reduction Software," by Brian Currier and Marta H. Fenn [AD-A192 094]

Report 4, "Demonstration of Instrumentation Automation Techniques at Beaver Dam, Eureka Springs, Arkansas," by Edward F. O'Neil [AD-A208 571]

REMR-CS-6
"In Situ Repair of Deteriorated Concrete in Hydraulic Structures: Feasibility Studies," by Ronald P. Webster and Lawrence E. Kukacka [AD-A182 297]

REMR-CS-7
"Design of a Precast Concrete Stay-In-Place Forming System for Lock Wall Rehabilitation," by ABAM Engineers, Inc. [AD-A185 081]

REMR-CS-8
"Procedures and Devices for Underwater Cleaning of Civil Works Structures," by Carmela A. Keeney [AD-A188 814]

REMR-CS-9
"Inspection of the Engineering Condition of Underwater Concrete Structures," by Sandor Popovics and Willie E. McDonald [AD-A208 295]

REMR-CS-10
"Development of Nondestructive Testing Systems for In Situ Evaluation of Concrete Structures," by Henry T. Thornton, Jr., and A. Michel Alexander [AD-A191 312]

REMR-CS-11
"In Situ Repair of Deteriorated Concrete in Hydraulic Structures: Laboratory Study," by Ronald P. Webster and Lawrence E. Kukacka [AD-A190 303]

REMR-CS-12
"Factors Related to the Performance of Concrete Repair Materials," by Lawrence I. Knab [AD-A192 818]

REMR-CS-13
"Rehabilitation of Navigation Lock Walls: Case Histories," by James E. McDonald [AD-A192 202]

REMR-CS-14
"A Demonstration of the Constructibility of a Precast Concrete Stay-in-Place Forming System for Lock Wall Rehabilitation," by ABAM Engineers, Inc. [AD-A195 471]

REMR-CS-15
"Analysis of Concrete Cracking in Lock Wall Resurfacing," by C. Dean Norman, Roy L. Campbell, Sr., and Sharon Garner [AD-A198 437]

REMR-CS-16
"Repair of Dam Intake Structures and Conduits: Case Histories," by Roy L. Campbell, Sr., and Dennis L. Bean [AD-A192 819]

REMR-CS-17
"Surface Treatments to Minimize Concrete Deterioration"

Report 1, "Survey of Field and Laboratory Application and Available Products," by Dennis L. Bean [AD-A195 069]

Report 2, "Laboratory Evaluation of Surface Treatment Materials," by Tony B. Husbands and Fred E. Causey [AD-A227 373]

REMR-CS-18
"Evaluation of Concrete Mixtures for Use in Underwater Repairs," by Billy D. Neeley [AD-A193 897]

REMR-CS-19
"Review of the State of the Art for Underwater Repair Using Abrasion-Resistant Concrete," by Ben C. Gerwick, Inc. [AD-A199 793]

REMR-CS-20
"Evaluation of Vinylester Resin for Anchor Embedment in Concrete," by James E. McDonald [AD-A206 847]

REMR-CS-21
"In Situ Repair of Deteriorated Concrete in Hydraulic Structures: A Field Study," by Ronald P. Webster, Lawrence E. Kukacka, and Dave Elling [AD-A208 913]

REMR-CS-22
"Monolith Joint Repairs: Case Histories," by James H. May and James E. McDonald [AD-A212 814]

REMR-CS-23
"Evaluation of Polyester Resin, Epoxy and Cement Grouts for Embedding Reinforcing Steel Bars in Hardened Concrete," by J. Floyd Best and James E. McDonald [AD-A218 347]

REMR-CS-24
"Reliability of Steel Civil Works Structures," by Paul F. Mlakar, Sassan Toussi, Frank W. Kearney, and Dawn White [AD-A212 922]

REMR-CS-25
"Spall Repair of Wet Concrete Surfaces," by J. Floyd Best and James E. McDonald [AD-A218 708]

REMR-CS-26
"Analysis of a Short Pulse Radar Survey of Revetments Along the Mississippi River," by Steven A. Arcone [AD-A213 501]

REMR-CS-27
"User's Guide: Maintenance and Repair Materials Data Base for Concrete and Steel Structures," by Richard L. Stowe and Roy L. Campbell, Sr. [AD-A220 386]

REMR-CS-28
"Concepts of Installation of the Precast Stay-in-Place Forming System for Lock Wall Rehabilitation in an Operational Lock," by ABAM Engineers, Inc. [AD-A220 399]

REMR-CS-29
"Methods of Evaluating the Stability and Safety of Gravity Earth Retaining Structures Founded on Rock," by R. M. Ebeling, G. W. Clough, J. M. Duncan, and T. L. Brandon [AD-A251 420]

REMR-CS-30
"In Situ Repair of Deteriorated Concrete in Hydraulic Structures: Epoxy Injection Repair of a Bridge Pier," by R. P. Webster, L. E. Kukacka, and D. Elling [AD-A229 429]

REMR-CS-31
"Evaluation of Civil Works Metal Structures," by Frederick H. Kisters and Frank W. Kearney [AD-A232 865]

REMR-CS-32
"Properties of Silica-Fume Concrete," by James E. McDonald [AD-A235 369]

REMR-CS-33
"Anchor Embedment in Hardened Concrete Under Submerged Conditions," by James E. McDonald [AD-A234 384]

REMR-CS-34
"Laboratory Evaluation of Concrete Mixtures and Techniques for Underwater Repairs," by Billy D. Neeley, Kenneth L. Saucier, and Henry T. Thornton, Jr. [AD-A231 195]

REMR-CS-35
"Predicting Concrete Service Life in Cases of Deterioration Due to Freezing and Thawing," by Larry M. Bryant and Paul F. Mlakar [AD-A235 616]

REMR-CS-36
"Evaluation and Repair of Concrete Structures: Annotated Bibliography 1978-1988," Vols I and II, by James E. McDonald and Willie E. McDonald [AD-A242 218—Vol I; AD-A242 219—Vol II]

REMR-CS-37
"Underwater Repair of Concrete Damaged by Abrasion-Erosion," by Kamal Henry Khayat [AD-A245 901]

REMR-CS-38
"Underwater Stilling Basin Repair Techniques Using Precast or Prefabricated Elements," by R. D. Rail and H. H. Haynes [AD-A245 900]

REMR-CS-39
"Continuous Deformation Monitoring System (CDMS)," by Carl A. Lanigan [AD-A261 833]

REMR-CS-40
"Impacts as a Source of Acoustic Pulse-Echo Energy for Nondestructive Testing of Concrete Structures," by A. Michel Alexander [AD-A264 368]

REMR-CS-41
"Comparison of Cast-in-Place Concrete Versus Precast Concrete Stay-in-Place Forming Systems for Lock Wall Rehabilitation," by William R. Miles [AD-A273 113]

REMR-CS-42
"Overlays on Horizontal Concrete Surfaces: Case Histories," by Roy L. Campbell, Sr. [AD-A276 952]

REMR-CS-43
"Structural Evaluation of Riveted Spillway Gates," by John E. Bower, Mark R. Kaczinski, Zouzhang Ma,Yi Zhou, John D. Wood, and Ben T. Yen [AD-A281 492]

REMR-CS-44
"Field Testing and Structural Analysis of Vertical Lift Lock Gates," by Brett C. Commander, Jeff X. Schulz, George G. Goble, and Cameron P. Chasten [AD-A281 491]

REMR-CS-45
"Detection of Structural Damage on Miter Gates," by Brett C. Commander, Jeff X. Schulz, and George G. Goble [AD-A285 248]

REMR-CS-46
"Repair and Maintenance of Masonry Structures: Case Histories," by Edward F. O'Neil [AD-A294 186]

REMR-CS-47
"Performance Criteria for Concrete Repair Materials, Phase I," by Peter H. Emmons and Alexander M. Vaysburd [AD-A295 136]

REMR-CS-48
"Evaluation of Injection Materials for the Repair of Deep Cracks in Concrete Structures," Paul D. Krauss, John M. Scanlon, and Margaret A. Hanson [AD-A302 262]

REMR-CS-49
"Applications of Precast Concrete in Repair and Replacement of Civil Works Structures," by James E. McDonald and Nancy F. Curtis [AD-A299 666]

REMR-CS-50
"A Conceptual Design for Underwater Installation of Geomembrane Systems on Concrete Hydraulic Structures," by J. Chris Christensen, Matthew A. Marcy, Alberto M. Scuero, and Gabriella L. Vaschetti [AD-A304 491]

REMR-CS-51
"A Constructibility Demonstration of Geomembrane Systems Installed Underwater on Concrete Hydraulic Structures," by Matthew A. Marcy, Alberto M. Scuero, and Gabriella L. Vashetti [AD-A320 679]

REMR-CS-52
"Results of Laboratory Tests on Materials for Thin Repair of Concrete Surfaces," by W. Glenn Smoak, Tony B. Husbands, and James E. McDonald [AD-A321 981]

REMR-CS-53
"Applications of Roller-Compacted Concrete in Rehabilitation and Replacement of Hydraulic Structures," by James E. McDonald and Nancy F. Curtis [AD-A326 634]

REMR-CS-54
"Evaluating the Stability of Existing Massive Concrete Gravity Structures Founded on Rock," by Robert M. Ebeling, Michael E. Pace, and Ernest E. Morrison, Jr. [AD-A329 714]

REMR-CS-55
"Evaluation of Criteria for Uniformity of Roller-Compacted Concrete," by Brian H. Green, Billy D. Neeley, and Toy S. Poole [AD-A341 119]

REMR-CS-56
"Evaluation of Grouting Materials for Anchor Embedments in Hardened Concrete," by Willie E. McDonald [AD-A337 585]

REMR-CS-57
"Performance Criteria for Concrete Repair Materials, Phase II Laboratory Results," by Randall W. Poston, Keith, E. Kesner, Peter H. Emmons, and Alexander M. Vaysburd [AD-A344 266]

REMR-CS-58
"Application of Artificial Neural Networks to Ultrasonic Pulse Echo System for Detecting Microcracks in Concrete," by A. Michel Alexander and Richard W. Haskins [AD-A347 421]

REMR-CS-59[1]
"Accuracy of Estimating Compressive Strength of Deteriorated concrete Seawall by Nondestructive Evaluation (NDE)," by A. Michel Alexander [AD-A352 602]

REMR-CS-60[1]
"Performance Criteria for Concrete Repair Materials, Phase II Field Studies," by Peter H. Emmons, Alexander M. Vaysburd, Randall W. Poston, and James E. McDonald [AD-A356 138]

REMR-CS-61[1]
"An Evaluation of Equipment and Procedures for Tensile Bond Testing of Concrete Repairs," by Alexander M. Vaysburd and James E. McDonald [AD-A366 843]

REMR-CS-62[1]
"Performance Criteria for Concrete Repair Materials, Phase II Summary Report," by Alexander M. Vaysburd, James E. McDonald, Randall W. Poston, and Keith E. Kesner [AD-A362 896]

REMR-CS-63[1]
"Repair and Rehabilitation of Dams: Case Studies," James E. McDonald and Nancy F. Curtis [AD-A372 898]

Unnumbered
"Proceedings of REMR Workshop on Assessment of the Stability of Concrete Structures on Rock, 10-12 September 1985," compiled by William F. McCleese [AD-A185 644]

Electrical and Mechanical Applications

REMR-EM-1
"A Review of Bird Pests and Their Management," by Anthony J. Krzysik [AD-A190 195]

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[1] Full text available on-line (in PDF format) at *http://www.dtic.mil/stinet/index.html*.

REMR-EM-2
"Evaluation of Bird Pest Problems at U.S. Army Corps of Engineers Civil Works Projects," by Anthony J. Krzysik [AD-A191 173]

REMR-EM-3[1]
"Underwater Applied Coatings: A State-of-the-Art Investigation," by R. W. Drisko and J. R. Yanez [AD-A201 712]

REMR-EM-4
"Hydroelectric Generator and Generator-Motor Insulation Tests," by Robert H. Bruck and Ray G. McCormack [AD-A212 924]

REMR-EM-5
"Lubricants for Hydraulic Structures," by Ward B. Clifton and Alfred D. Beitelman [AD-A213 260]

REMR-EM-6
"Mechanical Properties and Corrosion Behavior of Stainless Steels for Locks, Dams, and Hydroelectric Plant Applications," by Ashok Kumar, Ali A. Odeh, and J. R. Myers [AD-A219 490]

REMR-EM-7[1]
"High-Solids and 100-Percent Solids Coatings: A State-of-the-Art Investigation," by John Baker and Alfred D. Beitelman [AD A247 557]

REMR-EM-8[1, 2]
"Methods for Removal of Lead Paint from Steel Structures," by Lloyd Smith and Alfred Beitelman [AD-A317 426]

REMR-EM-9[1,2]
"Abrasion Resistant, Volative Organic Compound (VOC) Compliant Coatings for Hydraulic Structures," by Alfred D. Beitelman [AD-A306 376]

REMR-EM-10[1]
"High Solids and Zinc-Rich Epoxy Coatings for Corps of Engineers Civil Works Structures," by Alfred D. Beitelman and Dennis Huffman [AD-A308 768]

REMR-EM-11[1]
"Coatings for Use on Wet or Damp Steel Structures," by Alfred D. Beitelman [AD-A341 787]

Unnumbered
"Proceedings of REMR Workshop on Management of Bird Pests," by Anthony J. Krzysik [AD-A185 644]

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[1] Full text available on-line (in PDF format) *at http://www.cecer.army.mil/td/tips/browse/publications.cfm*.
[2] Full text available on-line (in PDF format) at *http://www.dtic.mil/stinet/index.html*.

Geotechnical Applications

REMR-GT-1
"Mathematical Analyses of Landside Seepage Berms," by Reginald A. Barron [AD-A150 014]

REMR-GT-2
"Improvement of Liquefiable Foundation Conditions Beneath Existing Structures," by Richard H. Ledbetter [AD-A160 695]

REMR-GT-3, "Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels"

Report 1, "Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels," by Christopher P. Cameron, Kerry D. Cato, Colin C. McAneny, and James H. May [AD-A173 163]

Report 2, "Analysis of Field and Laboratory Data," by Christopher P. Cameron, David M. Patrick, Kerry D. Cato, and James H. May [AD-A203 774]

Report 3, "Remediation," by Christopher P. Cameron, David M. Patrick, Craig O. Bartholomew, Allen W. Hatheway, and James H. May [AD-A203 775]

Report 4, "Geologic and Hydrodynamic Controls on the Mechanics of Knickpoint Migration," by James H. May [AD-A216 749]

Report 5, "Summary of Results, Conclusions, and Recommendations," by Christopher P. Cameron, David M. Patrick, James H. May, John B. Palmerton, Colin C. McAnany, Allen W. Hatheway, Craig O. Bartholomew, Christopher C. Mathewson, and Kerry D. Cato [AD-A228 781]

Supplement,[1] "Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels: Supplemental Information on Prediction, Control, and Repair of Erosion in Emergency Spillway Channels," by Christopher C. Mathewson, Kerry D. Cato, and James H. May [AD-A352 987]

REMR-GT-4
"State of the Art for Design and Construction of Sand Compaction Piles," by Richard D. Barksdale [AD-A188 816]

REMR-GT-5
"Inspection and Control of Levee Underseepage During Flood Fights," by Robert W. Cunny [AD-A188 324]

[1] Full text available on-line (in PDF format) at *http://www.cecer.army.mil/td/tips/browse/publications.cfm*.

REMR-GT-6
"Geotechnical Applications of the Self Potential (SP) Method"

Report 1, "The Use of Self Potential in the Detection of Subsurface Flow Patterns in and Around Sinkholes," by Ronald A. Erchul [AD-A194 524]

Report 2, "The Use of Self Potential to Detect Ground-Water Flow in Karst," by Ronald A. Erchul and Dennis W. Slifer [AD-A209 339]

Report 3, "Development of Self-Potential Interpretation Techniques for Seepage Detection," by Robert W. Corwin and Dwain K. Butler [AD-A207 704]

Report 4, "Numerical Modeling of SP Anomalies: Documentation of Program SPPC and Applications," by Michael J. Wilt and Dwain K. Butler [AD-A220 716]

REMR-GT-7
"Applications of the State of the Art of Stone Columns--Liquefaction, Local Bearing Failure, and Example Calculations," by Richard D. Barksdale [AD-A191 606]

REMR-GT-8
"Review of Consolidation Grouting of Rock Masses and Methods for Evaluation," by R. Morgan Dickinson [AD-A198 209]

REMR-GT-9
"A Survey of Engineering Geophysics Capability and Practice in the Corps of Engineers," by Dwain K. Butler, Ronald E. Wahl, Nolan W. R. Mitchell, and Gregory L. Hempen [AD-A194 520]

REMR-GT-10
"High-Resolution Seismic Reflection Investigations at Beaver Dam, Arkansas," by Thomas L. Dobecki, Tanya L. Mueller, and Monroe B. Savage [AD-A211 228]

REMR-GT-11
"Levee Underseepage Analysis for Special Foundation Conditions," by Thomas F. Wolff [AD-A213 500]

REMR-GT-12
"Re-Evaluation of the Sliding Stability of Concrete Structures on Rock with Emphasis on European Experience," by K. Kovari and P. Fritz [AD-A214 403]

REMR-GT-13
"Levee Underseepage Software User Manual and Validation," by Robert W. Cunny, Victor M. Agostinelli, Jr., and Hugh M. Taylor, Jr. [AD-A214 024]

REMR-GT-14
"Surface Roughness Characterization of Rock Masses Using the Fractal Dimension and the Variogram," by James R. Carr [AD-A225 384]

REMR-GT-15
"Plastic Concrete Cutoff Walls for Earth Dams," by Thomas W. Kahl, Joseph L. Kauschinger, and Edward B. Perry [AD-A234 566]

REMR-GT-16
"Redevelopment of Relief Wells, Upper Wood River Drainage and Levee District, Madison County, Illinois," by J. Kissane and Roy E. Leach [AD-A273 845]

REMR-GT-17
"Applications and Testing of Resin-Grouted Rockbolts," by Timothy S. Avery and James E. Friant [AD-A245 980]

REMR-GT-18
"Evaluation of the Rehabilitation Program for Relief Wells at Leesville Dam, Ohio," by Roy E. Leach and Glen Hackett [AD-A259 197]

REMR-GT-19
"DAMSEAL—An Expert System for Evaluating Dam Seepage," by Roger L. King and Wendell O. Miller [AD-B171 367]

REMR-GT-20
"Evaluation of Overturning Analysis for Concrete Structures on Rock Foundations," Shannon and Wilson [AD-A273 485]

REMR-GT-21
"Incorporation of Wall Movement and Vertical Wall Friction in the Analysis of Rigid Concrete Structures on Rock Foundations," Shannon and Wilson [AD-A273 009]

REMR-GT-22
"The State of Practice for Determining the Stability of Existing Concrete Gravity Dams Founded on Rock," by James K. Meisenheimer [AD-A298 577]

REMR-GT-23
"Design Procedure for Geosynthetic Reinforced Steep Slopes," by Dov Leshchinsky [AD-A321 646]

REMR-GT-24
"Use of Geocomposite Drainage Systems as a Temporary Measure to Improve the Surficial Stability of Levees," by Dov Leshchinsky [AD-A319 371]

REMR-GT-25
"Effects of Short Polymeric Fibers on Crack Development in Clays," by Stacy Shulley, Dov Leshchinsky, and Hoe I. Ling [AD-A337 814]

REMR-GT-26[1]
"Innovative Methods for Levee Rehabilitation," by Edward B. Perry [AD-A354 949]

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[1] Full text available on-line (in PDF format) at *http://www.dtic.mil/stinet/index.html*.

Unnumbered
"Proceedings of REMR Workshop on New Remedial Seepage Control Methods for Embankment-Dams and Soil Foundations," by Edward B. Perry [AD-A191 073]

Unnumbered
"Proceedings of REMR Workshop on Research Priorities for Drainage System and Relief Well Problems," by Roy E. Leach and Hugh M. Taylor, Jr. [AD-A212 067]

Unnumbered
"Proceedings of REMR Workshop on Levee Rehabilitation," Compiled by Edward B. Perry [AD-A285 413]

Hydraulics Applications

REMR-HY-1
"Annotated Bibliography for Navigation Training Structures," Compiled by Walter E. Pankow and Robert F. Athow, Jr. [AD-A173 30]

REMR-HY-2
"Floating Debris Control; A Literature Review," by Roscoe E. Perham [AD-A184 033]

REMR-HY-3
"Elements of Floating Debris Control Systems," by Roscoe E. Perham [AD-A200 454]

REMR-HY-4
"Effects of Geometry on the Kinetic Energy of a Towboat and Barges in a Navigation Lock," by Sandra K. Martin [AD-A207 057]

REMR-HY-5
"Explicit Numerical Algorithm for Modeling Incompressible Approach Flow," by Robert S. Bernard [AD-A207 176]

REMR-HY-6
"Inventory of River Training Structures in Shallow-Draft Waterways," by David L. Derrick, Herbert W. Gernand, and James P. Crutchfield [AD-A214 566]

REMR-HY-7
"Lock Accident Study," by Sandra K. Martin and Martin E. Lipinski [AD-A228 627]

REMR-HY-8
"Shallow-Draft Training Structure Current Repair Practices and Repair Guidelines," by David L. Derrick [AD-A239 045]

REMR-HY-9
"Design Criteria for Lateral Dikes in Estuaries," by R.C. Berger and M. P. Alexander [AD-A275 317]

REMR-HY-10
"Icing Problems at Corps Projects," by F. Donald Haynes, Robert Haehnel, and Leonard Zabilansky [AD-A266 343]

REMR-HY-11
"STREMR: Numerical Model for Depth-Averaged Incompressible Flow," by Robert S. Bernard [AD-A269 949]

REMR-HY-12
"HIVEL2D: A Two-Dimensional Flow Model for High-Velocity Channels," by R.L. Stockstill and R.C. Berger [AD-A286 556]

REMR-HY-13
"HIVEL2D User's Manual," by R.C. Berger, Richard L. Stockstill, and Mikel W. Ott [AD-A301 541]

REMR-HY-14
"Ice Control Techniques for Corps Projects," by F. Donald Haynes, Robert Haehnel, Charles Clark, and Leonard Zabilansky [AD-A301 541]

Unnumbered
"Proceedings of REMR Workshop on Repair and Maintenance of Shallow-Draft Training Structures," Compiled by David L. Derrick [AD-A235 666]

Operations Management

REMR-OM-1
"Evaluation of Existing Condition Rating Procedures for Civil Works Structures and Facilities," by Enno Koehn and Anthony M. Kao [AD-A170 391]

REMR-OM-2
"REMR Management System," by H. Thomas Yu and Anthony M. Kao [AD-A200 728]

REMR-OM-3
"User's Manual: Inspection and Rating of Steel Sheet Pile Structures," by Lowell Greimann and James Stecker [AD-A210 411]

REMR-OM-4
"A Rating System for the Concrete in Navigation Lock Monoliths," by Rupert E. Bullock [AD-A208 304]

REMR-OM-5
"Timber Dike Management System," by H. Thomas Yu and Anthony M. Kao [AD-A213 851]

REMR-OM-6
"Network Level REMR Management System for Civil Work Structures: Concept Demonstration on Inland Waterways Locks," by Michael J. Markow, Sue McNeil, Dharma Acharya, and Mark Brown [AD-A217 031]

REMR-OM-7
"Inspection and Rating of Miter Lock Gates," by Lowell Greimann, James Stecker, and Kevin Rens [AD-A227 198]

REMR-OM-8
"REMR Management Systems--Navigation Structures: Management System for Miter Gates," by Lowell Greimann, James Stecker, and Kevin Rens [AD-A231 469]

REMR-OM-9
"Maintenance and Repair of Steel Sheet Pile Structures," by Lowell Greimann and James Stecker [AD-A231 916]

REMR-OM-10
"Lockwall: A Microcomputer-Based Maintenance and Repair Management System for Concrete Navigation Lock Monoliths," by David T. McKay and Anthony M. Kao [AD-A228 625]

REMR-OM-11
"REMR Management Systems--Coastal/Shore Protection Structures: Condition Rating Procedures for Rubble Breakwaters and Jetties-Initial Report," by Donald E. Plotkin, D. D. Davidson, and Joan Pope [AD-A237 042]

REMR-OM-12
"REMR Management Systems--Navigation Structures: Users Manual for Concrete Navigation Lock Monoliths," by Automation Support Center, University of Illinois, and David T. McKay [AD-A248 994]

REMR-OM-13
"REMR Management Systems--Navigation Structures: Condition Rating Procedures for Sector Gates," by Lowell Greimann, James Stecker, and Kevin Rens [AD-A279 299]

REMR-OM-14
"REMR Management Systems--Navigation Structures: Condition Rating Procedures for Tainter and Butterfly Valves," by Lowell Greimann, James Stecker, and Joel Veenstra [AD-A279 326]

REMR-OM-15
"REMR Management Systems--Navigation Structures, User's Manual for Inspection and Rating Software, Version 2.0," by Lowell Greimann, James Stecker, Kevin Rens, and Mike Nop [AD-A282 219]

REMR-OM-16
"REMR Management Systems--Navigation and Reservoir Structures, Condition Rating Procedures for Concrete in Gravity Dams, Retaining Walls, and Spillways," by Rupert E. Bullock and Stuart D. Foltz [AD-A303 305]

REMR-OM-17[1]
"REMR Management Systems--Navigation Structures, Condition Rating Procedures for Tainter Dam and Lock Gates," by Lowell Greimann, James Stecker, and Mike Nop [AD-A303 294]

REMR-OM-18
"REMR Management Systems--Navigation Structures, Condition Rating Procedures for Roller Dam Gates," by Lowell F. Greimann, James H. Stecker, Timothy A. Kraal, and Stuart D. Foltz [AD-A330 894]

REMR-OM-19[1]
"REMR Management Systems--Navigation and Flood Control Structures, Condition Rating Procedures for Lock and Dam Operating Equipment," by James H. Stecker, Lowell F. Greimann, Scott Mellema, Kevin Rens, and Stuart D. Foltz [AD-A330 934]

REMR-OM-20[1,2]
"REMR Management Systems--BREAKWATER Computer Program User Manual (Version 1.0)," by Ricardo Aguirre and Don Plotkin [AD-A352 558]

REMR-OM-21[1,2]
"REMR Management Systems—Navigation Structures: A Simple Condition and Performance Rating Procedure for Riverine Stone Training Dikes and Revetments," by David T. McKay [AD-A355 567]

REMR-OM-22[1,2]
"REMR Management Systems—Navigation and Flood Control Structures: User's Software Manual for Inspection and Rating of Concrete in Gravity Dams, Retaining Walls, and Spillways," by Stuart D. Foltz [AD-A356 606]

REMR-OM-23[1,2]
"REMR Management Systems—Riverine Dike and Revetment Condition Index Software (DIKE_CI) User's Manual," by David T. McKay and John M. Elston [AD-A355 814]

REMR-OM-24[1]
"REMR Management Systems—Coastal/Shore Protection Structures: Condition Rating Procedures for Rubble Breakwaters and Jetties," by J. Oliver, D. Plotkin, J. Lesnik, and D. Pirie

[1] Full text available on-line (in PDF format) at *http://www.cecer.army.mil/td/tips/browse/publications.cfm*.
[2] Full text available on-line (in PDF format) at *http://www.dtic.mil/stinet/index.html*.

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Appendix C Listing of REMR Videos[1]

REMR Video-CS-1
"Remedial Waterstop Installation at Pine Flat Dam," Dec 1986, 13 min, 1/2-in. (see *The REMR Bulletin*, Vol 2, No. 3).

REMR Video-CS-2
"Precast Concrete Stay-in-Place Forming System for Lock Wall Rehabilitation," July 1988, 20 min, 1/2- and 3/4-in.

REMR Video-CS-3
"Antiwashout Admixtures for Use in Underwater Concrete Placement," May 1989, 15 min, 20 sec, 1/2-in.

REMR Video-CS-4
"Comparison of Cast-in-Place Concrete Versus Precast Concrete Stay-in-Place Forming Systems for Lock Wall Rehabilitation-Troy Lock and Dam," Feb 1993, 20 min.

REMR Video-CS-5
"Underwater Installation of Geomembrane Systems on Concrete Hydraulic Structures," Jan 1997, 9 min.

REMR Video-EM-1
"REMR I Summary of Electrical and Mechanical Problem Area"

REMR Video-GT-1
"Computer Monitoring of Foundation Grouting," June 1986, 10 min., 1/2- and 3/4-in.

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[1] REMR technology videos are available through the Inter-Library Loan Service. Local librarians can request copies of the videos by contacting the Technical Library of the U.S. Army Engineer Research and Development Center, Vicksburg, MS, at (601) 634-2571. REMR videos may be copied and used for private viewing, classroom instruction, or presentation.

REMR Video-HY-1
"Excessive Scour Downstream of High Level Emergency Spillways," Oct 1987, 20 min, 1/2- and 3/4-in.

REMR Video-PM-1
"Overview of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program," Apr 1985, 17 min, 30 sec.

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14. ABSTRACT

This report summarizes the research conducted as part of the U.S. Army Corps of Engineers' Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program and is intended to serve as a guide to accessing REMR technology.

The primary objective of the program was to identify and develop effective and affordable technology for maintaining and extending the service life of existing Corps civil works structures. For management purposes, the program was broken down into seven broad problem areas: Concrete and Steel Structures, Geotechnical, Hydraulics, Coastal, Electrical and Mechanical, Environmental Impacts, and Operations Management.

The REMR Program was conducted in two phases, beginning in fiscal year (FY) 1984. Phase 1 of the program was a 6-year, $35-million effort that was completed in FY 1989. This phase clearly demonstrated the benefits of research in getting more value for the dollars spent on REMR activities. The estimated dollar savings from the use of the research results exceeded $200 million over a 5-year period following completion of the Phase 1 effort.

(Continued)

15. SUBJECT TERMS

Coastal applications, Concrete and steel structures, Electrical and mechanical applications, Environmental impacts, Evaluation, Geotechnical applications, Hydraulics applications, Maintenance, Rehabilitation, Repair

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Due to the successes of the Phase 1 effort and the opportunity for similar successes on other REMR-type problems, Phase 2 of the program was initiated in FY 1991 and was completed in FY 1998 at a cost of $31.2 million. The dollar savings from the use of the Phase 2 research results are estimated to be similar to those achieved from the Phase 1 research.

Dollar savings attributed to use of REMR technology from both phases are expected to continue to accumulate for many more years.