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Condition Index Assessment for U.S. Army Corps of Engineers Civil Works

By David T. McKay,[1] Member, ASCE, Kevin L. Rens,[2] P.E., Associate Member, ASCE, Lowell F. Greimann,[3] Fellow, ASCE, and James H. Stecker[4]

Abstract: The U.S. Army Corps of Engineers is developing uniform condition assessment procedures for many of its civil works structures. The collected data are to be used in conjunction with other methodologies to focus and prioritize operations and maintenance expenditures for a wide variety of a large number of (often multipurpose) structures. The condition assessment is based upon objective and repeatable measurements, which, when processed by an algorithm, produce a numeric indicator, the Condition Index (CI). The CI is a number between 0 and 100 that is a gauge of the physical deterioration of a structure. For many structural components the CI also serves as an index of functional performance. As an indicator of the condition of the structure (or functionality) the CIs are useful to maintenance managers and engineers at all hierarchical levels of management within the Corps. This article reviews the inception, approach, development, and current status of the Corps of Engineers CI program. Illustrative examples describing the development of CI inspection methods and rating algorithms are provided for steel sheet pile and lock miter gate inland navigation structures. The expected and realized benefits from the implementation of CI inspections are enumerated. The goal of forecasting economic returns on investments in the operation and maintenance of civil works projects is also discussed.

USACE CIVIL WORKS

The U.S. Army Corps of Engineers (USACE) Directorate of Civil Works is under the command of Major General Russell Fuhrman, and employs approximately 27,000 people working in the eight divisions, 38 districts, and the U.S. Army Engineer Research and Development Center (USAERDC), which comprises four major laboratories and various activity centers.

Civil works structures are operated to maintain navigable waterways, reduce flood damage, protect coastal shores, generate hydropower, manage recreation areas, and support the [illegible] of public lands. In the inland navigation business area the Corps operates roughly 270 locks and [illegible] Several thousand dikes, revetments, breakwaters, miles of levees, and hundreds of reservoirs provide navigation channel maintenance, flood control, and shore protection. The Directorate of Civil Works is responsible for approximately 1670 inland and coastal ports and harbors. Managing the operations and maintenance (O&M) of this inventory is a monumental task. Of note, by the year 2000, 50% of the Corps' navigation locks and dams will have reached their design life (McDonald and Campbell 1985).

OPERATIONS MANAGEMENT IN CIVIL WORKS

The Corps of Engineers Division of Construction Operations and Readiness has been focusing research and development (R&D) dollars on methodologies that extend the service life of existing structures. In conjunction with this work, R&D efforts are also focusing on the development of tools to forecast the economic benefits of, and evaluate the cost effectiveness of, O&M expenditures. Such tools are necessary to justify the use of money in an environment where maintenance actions are deferred because of the lack of sufficient funds.

With limited and shrinking funds, the need to prioritize O&M dollars is becoming increasingly difficult for districts with a variety of facilities with differing functions. How are conditions related to overall project performance? (For this paper a project may be considered to be an inland navigation pool and the structures associated with it, or perhaps a watershed with flood control structures and several recreation areas.) What is the best use of available dollars? On a national level USACE headquarters faces the same problem from two ends: with its congressional appropriation, and when it distributes the appropriation among districts, divisions, and various activ[illegible]

With a focus on extending service life [illegible] [illegible] budgets with data driven decisions [illegible] more effectively focusing O&M dollars [illegible] operations management is being acco[illegible] USAERDC. The early successes of O&[M] [sys]tems such as for pavements (PAVER) (Sh[illegible] and roofing (ROOFER) (Shahin et al. [illegible] motivated the development of similar sy[stems for] civil works structures. The resulting pro[illegible] based condition assessment procedures, [illegible] of engineering judgement. The rudiment[illegible] systems is that O&M management mus[illegible] knowledge of the structure's condition a[illegible] several years from now. If reliable curv[illegible] levels versus time are available, predic[illegible] grams can be planned. Precious mainte[illegible] focused where the benefits are optimize[illegible]

Though still far from these ultimate [illegible] systems have proven useful in other wa[illegible] tures are continuously monitored when [illegible] occurs and is documented every five ye[illegible] the periodic inspection. The inspectio[illegible] dozen or more people with expertise in [illegible] electrical, hydraulic, and geotechnical e[illegible] and preinspection materials are provide[illegible] inspector. These inspections are typ[illegible] through. Visual observations, though ex[illegible] corded in ways that might be consider[illegible] not intimately familiar with the structu[illegible] and repeatability found in tangible meas[illegible] scribed procedures that bring usefulne[illegible] systems.

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One extra benefit derived from the development of these tools is the capture of institutional knowledge that often retires along with those learned employees leaving service. Recorded rules and procedures are excellent ways to educate younger engineers.

Expert rules in the form of equations and/or tables are combined, and inspection procedures with emphasis on tangible quantitative measurements are developed. Whenever possible, inspection procedures are designed to be performed on in-service facilities. Simple, easy to obtain measurements are used. Objectivity is the goal, but subjective observations cannot be completely avoided and are used as seldom as possible. Inspections for all component systems developed to date can be completed in hours. To date, C-clamps, magnets, dial gauges, tape measures, rod and transit, or a boat equipped with a depth finder have been the extent and sophistication of the inspection equipment needed. Equally important, the procedures must be repeatable. That is, different inspection teams must produce comparable results. All calculated and tabulated results are scaled to conform to the CI definition, described below.

CONDITION INDEX

Table 1 illustrates the Condition Index (CI) Scale. The CI is a number from 0 to 100 and is indicative of a structure's condition. This definition provides a consistent language or definition with which to discuss conditions. Using a number to describe conditions has the obvious advantages of being easily stored in a computer and can be manipulated in mathematical expressions. The CI is based on structural integrity and on the ability of a structure to perform its function.

The CI has three action zones and seven condition levels. The purpose of the CI is to capture a "snapshot" of condition. The intent, when building the CI algorithms, is to capture as pure a picture of condition as possible. Researchers try to avoid incorporating predictive parameters in the CI, such as consequences of failure or what "might be" in the future. E.g., two structures of identical condition might have entirely different consequences of failure, yet their CIs will be the same. The CI should be likened to unbiased factual reporting. It should indicate what happened, but it should not endeavor to predict what will follow; it should simply answer the question, what are the facts at this instant in time? Although safety and serviceability are incorporated into the procedures, the CI should not be interpreted as an absolute indicator of a structure's need of repair. This ultimate decision is up to expert (and human) judgment. However, for many of the structures on which the CI assessments are performed, the condition level relates more or less to its functional level, and only to this extent does the CI have predictive qualities. (For an example of a structure whose condition does not necessarily relate one on one with functionality, consider a navigation training dike, or breakwater, or levee. All may be in as-built condition, but how well they function may depend on ambient conditions that may have changed since construction.) These inspection procedures and resulting CIs do not comprise a comprehensive management system in the sense of including recommendations based upon the CIs, including work plans, condition prediction, budget forecasts, and more. But the O&M process is facilitated by these procedures and more comprehensive systems can be readily built around them.

These systems require some amount of preparation and execution time. For miter lock gates (which consist of two leaves are hinged about vertical axes at the lock walls, are located on both ends of the lock chamber, and are called miter gates for their similarity to the peaked miter cap worn by a pope or bishop when closed), about 6 hours are needed to fully inspect one set of gates and operating equipment, or 12 hours per lock. Yet even this system is based on simple observations and measurements of the gate in the normal operating mode. First-time execution takes longer, but once the learning curve is worked through these systems are very easy to use. Other systems may require more but most require a smaller investment of time. Nearly all of the inland navigation systems developed thus far have a similar "look and feel," and the transition from one system to another is sufficiently seamless. Evaluation of the results is supported by documentation and software.

The following sections detail the approach, development, difficulties, and lessons learned in a program that produced many useful CI products over the last decade. The writers describe the evolution of the CI development process that was used for the majority of inland navigation structures. The extrapolation to CI development for structure types common to other civil works business areas (e.g., flood damage reduction, hydropower, or recreation) is not exactly linear; however, the general idea is the same. Directions for further investigation and development are also presented.

General Approach

At the beginning of the project, it was clear that the source of knowledge for the condition assessment system development would be Corps of Engineers personnel (hereafter referred to as "experts") who had extensive experience with the various navigation structures. The challenge was to tap that source of knowledge, obtain a consensus of the experts, and formulate a consistent and unified assessment system. As each individual system was developed, changes could be incorporated only after a consensus was reached.

After some trial and error in the initial stages, a general procedure was eventually developed and applied to most civil works structures. Some evolutionary changes did occur, of

TABLE 1. Condition Index Scale

Zone (1)	Condition index (2)	Condition description (3)	Recommended action (4)
1	85 to 100	Excellent: No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 to 84	Good: Only minor deterioration or defects are evident.	
2	55 to 69	Fair: Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 to 54	Marginal: Moderate deterioration. Function is still adequate.	
3	25 to 39	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
	10 to 24	Very Poor: Extensive deterioration. Barely functional.	
	0 to 9	Failed: No longer functions. General failure or complete failure of a major structural component.	

course, during the project, and the major ones are pointed out below.

Initial Site Visits

During the site visit stage, the research team visited several sites with representative structures to: (1) familiarize the research team with the structure and its operation; (2) interview the site experts to identify distresses; and (3) learn current inspection/evaluation methods. Experts who met with the research team included engineers and managers from the Engineering and Operations Divisions, as well as site operators and mechanics from the various projects.

As an introduction, the team explained the purpose of the visit and the general concept of a condition index assessment. During these visits, the team would discuss with the experts the important attributes of the structures. This part of the project always elicited many interesting question and answer sessions, such as the following:

- What are the distresses associated with the structures?
- How does the structure deteriorate?
- What things are now inspected and how?
- What are first indicators that something is going wrong?
- What are examples of things that until now have gone undetected?
- How and what could be inspected to detect problems missed up to now?
- How bad must the distresses become before the experts become concerned?
- How bad must the distresses become before the situation becomes critical?
- What is the meaning of "bad" and "good"?

These were very much listening sessions during which the research team encouraged the experts to express as many opinions and ideas as possible.

Generally, three or four such sites were visited for each type of component system. During the course of the project, at least 100 different sites were visited. Often, experts at the various sites expressed quite different opinions. In some cases, the districts treated the same problem differently. In many cases, the priority of problems was different.

An early and near continuous difficulty encountered by the research team came in confronting the strong concerns and reservations held by the expert panels regarding the eventual use of the CI system. A consistent fear was expressed that the systems would eventually be used by Corps leadership to "automate" or otherwise dictate to these very people the manner in which planned, scheduled, and executed their jobs. Although this concern did not ultimately affect the way in which the research was conducted or the final form of the product, it is informative to note the universal nature of the concern throughout the development process. Although the explanation offered by the team to allay such fears was generally held as suspect by most of the experts, it has proven to be valid and true: the CI systems are simply a small part of a larger tool set being produced to assist in the enormously difficult management of the O&M program in civil works. The systems are designed to be beneficial and useful at all operational levels within the organization, from the field up to headquarters. As demonstrated later in this paper, the CI systems have improved the job performance (by diagnosing potential problems early, appropriately reprogramming maintenance funds, and increasing safety levels) of those who most feared it.

Tentative Inspection Process

After the series of site visit, the project team began to select the important distresses identified by the experts, the cause and effect of the distresses, the parameters that described the distress, and the methods to measure the parameters. Some distresses were obviously important because experts consistently identified them. Others were important at some sites but not at others. The research team identified a tentative set of characteristics of the structure that would, if known, give a consistent measure of its condition.

An extremely important feature of all of the inspection techniques developed by the research team at Iowa State University was the measurement of structural response. For each of the structures that were investigated, the research team developed techniques that measured the behavior of the component under load. As much as possible, the loading conditions were those experienced during operation. For example, for miter lock gates, gate movements were recorded with the lock chamber at low pool (minimum load) and at upper pool (maximum operating load). In some cases where real loading was not possible, such as dewatered valves or sector gates, loads were applied with hydraulic jacks.

Another very important criterion for the inspection process was that project operation would be minimally disrupted. The inspection must be conducted with the lock and dam in an operating mode. Minimal holds on traffic for a few minutes would be permitted. In ... were acceptable, but no ... delay ... were ... In addition, the inspection was to be at a level such that ... technicians and lock personnel could conduct it. Engi... would not be needed.

With all these constraints, the research team devoted considerable effort to developing inspection and measure... techniques to gather the needed data. In many cases, the ... would develop alternate methods of measuring certain pa... eters and conduct additional site visits on their own to com... the methods and select one or two for further refinemen...

At this stage of development, tentative inspection form... field recording of the data were also developed.

Tentative Rule Set

A tentative set of condition assessment rules was formu... after the site visits and discussions with the experts. For ... distress and associated inspection measurement, the res... team asked the experts to relate the measurement to the ... dition index scale in Table 1. A critical question was, "... bad must the distress become before the condition of the ... ture is poor (a threshold condition index of 39 or 40)? ... example, "How big can a measurable gap between the ... blocks of a horizontally-framed, miter lock gate become ... a detailed engineering evaluation is required?" (Quoin ... are vertically aligned and matched bearing surfaces of ste... transfer loads upon a lock gate into the concrete suppo...

Typically, X identified the inspection measureme... quantified a distress (described in the previous sectio... value of X at which the condition of the component ... poor was identified by X_{max}, the limiting value of the ... Often, because of the diversity of opinion expressed a... visits, the research team could only establish tentative ... of X_{max} at this stage.

The system had to be adaptable to different types of ... conditions and structural configurations. For example, ... lift locks the limiting measurement X_{max} for bearing blo... in miter lock gates was different than it was for high li... (Lift is the difference in elevations of the headwater ... pool above the tailwater of the next. Lifts vary from ... to over 100 ft within the United States.)

A simple empirical formula was developed to relate ... tress measurement, X, and the limiting value, X_{max}, to ... tress condition index. The formula had to (1) give a c... index of 100 if there was no distress ($X = 0$); (2) giv... dition index of 40 if the distress was at its limiting ...

$= X_{max}$); and (3) give a decreasing value but greater than zero as the distress measurement, X, increased. The resulting, somewhat arbitrary formula was

$$\mathrm{CI}_i = 100(0.4)^{X_i/X_{i\,max}} \tag{1}$$

A number of possible distresses (between five and 15) were identified for each structure, each with its associated condition index given by (1). The combined condition index of the structure was taken to be a linear weighted combination of the individual distress in the following equation:

$$\mathrm{CI}_{\mathrm{Combined}} = \sum_{\mathrm{Distresses}} (W_i)(\mathrm{CI}_i), \quad 0 \le \mathrm{CI}_{\mathrm{Combined}} \le 100 \tag{2}$$

The W_i values represented weighting factors that established the relative importance of the individual distresses. Clearly, some distresses have a larger bearing on the structural condition assessment than others. Typically, the values of the weighting factors were established by the experts during the field testing, although tentative values were sometimes estimated at this stage.

If time and resources permitted, the research team applied the tentative inspection process and rule set at a convenient site. Several evolutionary changes were made during and after these visits.

Field Tests and Calibration

After a tentative inspection process and set of rules had been established by the research team, the next stage was to conduct a field test of the entire process. A team of experts would be assembled at a common site. Insofar as reasonable, the experts represented different areas of the country and varying experience with structural configurations. The group comprised managers, engineers, lockmasters, and lock operators or mechanics. Ideally, a collection of projects was selected to include a variety of structures (say, several miter gates) with a variety of distresses to test the process over the complete range.

At the beginning of the field test, the research team would explain the tentative formulations and the inspection process. The expert team would then conduct an inspection. Quite often, during this initial attempt, some problems with the tentative inspection process would become obvious. Some measurement techniques were determined to be flawed. Improvements were made in the field or further developed back in the office.

After the experts had made the measurements and while they were at the structure site, they would subjectively rate the condition of the structure. That is, for each of the distresses, the experts would use their engineering judgment to select a corresponding distress CI_i using the word description in Table 1. Using their individual opinions, the experts listed their set of relative weighting factors for (2). They also individually selected a combined CI, $\mathrm{CI}_{\mathrm{Combined}}$, for the entire structure, again using Table 1.

Following the inspection and field rating of the structure, the expert panel would assemble to discuss the results of the field test. These were some of the most interesting sessions of the project. The diversity of opinion on several topics became apparent. Again, since the objective was a reasonably consistent and uniform rating system, it was necessary to come to some consensus at the end of the field testing stage.

The distress CI_is from the tentative rules [(1)] were each compared to the experts' field-selected distress CI_is. Discrepancies were discussed. Should X_{max} be adjusted to calibrate the rules with the experts' opinion? Should X_{max} depend upon structural configuration? Are we measuring the right thing or are there better ways to characterize this distress (better X values)?

Several other issues would be brought to the table. Is the list of distresses complete? Do all of the distresses still seem important? How do we handle distresses that are not easily measured, such as corrosion? What about nonstructural features like paint and lubrication systems? The main objective had to be kept in mind: How best to gauge the physical deterioration of this structure or component?

The calculated $\mathrm{CI}_{\mathrm{Combined}}$ for the structure [(2)] was compared to the combined CI that the experts assigned at the site. Again discrepancies were discussed and resolved, insofar as possible. Many times the question "Should weighting factors be changed?" had to be discussed. In reality, this step was seldom completed during the field test. Because of adjustments that were needed in the calibration of the rules for the distresses, there was seldom time during the field test to complete the calibration of the $\mathrm{CI}_{\mathrm{Combined}}$. This step was most often completed by mailings and telephone calls.

The final comparisons of the distress CI_is and the $\mathrm{CI}_{\mathrm{Combined}}$ with the opinion of the experts were summarized in bar charts. A 100% agreement being unrealistic, the research team was satisfied if the algorithm consistently coincided with the experts subjective analyses to within 15 points or less. Generally the results were quite good and most often came much closer. Consensus was achieved on a vast majority, but not all, of the issues. Everyone recognized that this was development process that could be improved as it was applied.

Necessary Changes in Approach

During the evolution of the condition assessment process, many changes occurred. Most of these changes dealt with particular details and rule changes for the individual components. However, fundamental changes in direction occurred that affected the development of CI systems for all structures.

It become readily apparent after very limited field testing of the first structure (steel sheet pile) that the weighting factors in (2) are not really constant. As a particular distress became worse and approached the critical stage, the experts judged that its importance became more and more significant. In other words, its relative weight within the $\mathrm{CI}_{\mathrm{Combined}}$ increased and became more dominant as the distress CI_i approached zero. To account for this observation, a weight adjustment factor, AF_i, was introduced that increased the relative weight of a particular distress by a factor of eight if the distress CI_i was 39 or less (Zone 3 in Table 1). If the distress CI_i was in Zone 1 (above 69) no adjustment was necessary. In Zone 2, the adjustment factor was taken, quite arbitrarily, to vary linearly.

$$\mathrm{AF}_i = 8 - 7\left[\frac{\mathrm{CI}_i - 40}{30}\right], \quad 40 \le \mathrm{CI}_i \le 69 \tag{3}$$

The adjustments factor (AF_i) concept is applied universally to all inland navigation structures developed thus far. The remaining W_is are renormalized accordingly.

Another major change in the $\mathrm{CI}_{\mathrm{Combined}}$ related to what the experts called "critical distresses," such as structural cracks. For such critical cases, the experts decided that the $\mathrm{CI}_{\mathrm{Combined}}$ would not be calculated by the weighted combination (2) but that it would be set equal to the critical distress CI_i. For example, if structural cracks gave a crack distress CI_i of 30, the $\mathrm{CI}_{\mathrm{Combined}}$ of the structure would be 30.

A further major change related to safety and serviceability aspects of structural performance. In the initial work, two separate combined CIs were calculated: (1) a structural condition index $\mathrm{CI}_{\mathrm{Combined-S}}$ that was a measure of the safety, i.e., the performance of the structure at loads beyond normal operating levels; and (2) a functional condition index $\mathrm{CI}_{\mathrm{Combined-F}}$ that was a measure of the serviceability of the structure, i.e., the performance of the structure under normal operating conditions.

The $CI_{Combined\text{-}S}$ was related to the calculation of a traditional factor of safety using current design methods. The $CI_{Combined\text{-}F}$ was more subjective in nature and involved "engineering judgment." It took the form of (1).

As the development process proceeded, it was soon apparent that the experts took many factors into account as they evaluated the $CI_{Combined\text{-}F}$. In addition to the operating performance characteristics, they also incorporated judgments on the structural safety. Inspection observations indicated that a safety problem was likely or was in the process of developing and may soon become critical. Such observations were more indicative of structural safety than most simple factor of safety calculations. In addition, in cases such as miter lock gates, the factor of safety criteria did not more than compare the as-built structure to current code criteria. Distresses such as bearing block gaps in miter gates cold not be simply incorporated into the factor of safety calculations.

Ultimately, and somewhat later on during field testing, the ... inspected and rated by the experts ... follows the form outlined in the approach session. For example, the final consensus values for X_{max} for misalignment ranged from 0 in. for SSP walls in a lock chamber to 40 in. for retaining walls more than 500 ft from the lock chamber. The experts established the W_i [(2)] for misalignment as 24%. The final report compares the $CI_{Combined}$ calculated by the rules to that derived from the experts' judgment. In general, the research team and the experts were satisfied in this example if the two values compared within 15 points on the 100 point CI scale.

It was during the SSP condition assessment development that the adjustment factor in (3) was found to reasonably reflect the experts' judgment.

Two combined CI's (structural and functional) were developed for SSP structures. (The decision to drop development of $CI_{Combined\text{-}F}$ had not yet been made; see the Approach section.) The structural $CI_{Combined\text{-}S}$ was based on a structural analysis of the SSP structure. Factors of safety were calculated for three failure modes for walls (sheet bending, anchor tension, and foundation soil) and for four modes for cells (cell soil, sliding, bursting, and foundation soil). Condition assessment procedures were developed for SSP cantilevered and anchored walls, SSP single cells, and SSP cell walls.

Miter Lock Gates and a New Challenge

... the development team followed the procedures outlined above and prior to the general procedures, visited with senior leaders in the Great Lakes & Ohio River Division (LRD). At this meeting, it was brought to the attention of the research team that a miter gate system would be much more difficult to develop than was the SSP system. In fact, one of the senior leaders strongly doubted that it could be accomplished. The most critical comment at this meeting was the fact that the gates are unique from District to District—high lift gates in the Nashville District do not function, operate, or deteriorate the same way as low-lift gates in the Rock Island District. Clearly, the miter gate system was going to be a much greater challenge.

Because of its close proximity to Iowa State University, several preliminary site visits were made to the Rock Island District on the Upper Mississippi River in Illinois (Fig. 1). In addition, a dewatering at the Old Hickory lock and dam in Nashville District brought light to the concerns raised at the LRD project "kick off" meeting. Specifically, the Rock Island District gates were all low-lift lock chambers (less than 10 ft) as compared to the Old Hickory lock, which stood nearly 10 stories high in the dewatered state. In addition, it became clear upon interviewing the lock personnel at various sites in each

early input as to how best to proceed. The team visited the Peoria Lock and Dam site on their own to familiarize themselves with SSP retaining walls and cells. Further site visits were conducted in the Pittsburgh and the Louisville Districts. The experts identified the significant distresses for SSP structures as misalignment, corrosion, settlement, interlock separation, holes, dents, and cracks.

As an illustrative example, the misalignment distress was indicative of a structural or soil failure and, depending on location, had a large impact on the functionality of the SSP structure. The experts decided that misalignment could be measured by the deviation of the SSP, both horizontally and vertically, from the planned alignment. The inspection form included a log of the deviation and its extent [the X value in (1)] with station location. Measurements were made with a tape measure.

The research team selected a tentative set of X_{max} values for misalignment that varied with wall function and distance from the lock chamber. ... experts' confidence ... many safety issues were embedded in the $CI_{Combined\text{-}F}$ and since ... had several shortcomings ... to discontinue development of ... A subset of distresses were identified for each structure that had a particular bearing on safety and were called structural distresses. The structural distresses are flagged as safety issues if they exceed certain bounds established by the experts.

Computer Software

PC-based software was written to support the condition assessment process. The software for each of the structures has the same basic organization. After selecting the structure name from a preloaded Corps list, the user entered the inspection data following a layout that matched the inspection form layout. Once the inspection data was complete, the user requested that the software calculate the distress and combined condition indexes. Printed reports were requested. The software contained a consequence modeling module which allowed the user to ask "what if" questions, i.e., how would the CIs change if various repair scenarios were implemented. (Initial software versions included a maintenance and repair analysis module to compare the economic benefits of various repair options, but this module was discontinued in later versions because the analysis models used were too simple. More practical models and software platforms are the topic of ongoing research.)

Steel Sheet Pile

To a very large extent the approach outlined above came into being during the condition assessment development of the first two structures that were considered, steel sheet pile (SSP) structures and miter lock gates. SSP was selected as the first structure because of its apparent simplicity. SSP structures do not have "moving parts" and have fewer components than the other structures. At the same time, they introduced many of the challenges that occurred in all the structures, such as:

- How do you identify components?
- How do you handle corrosion?
- How do you inspect what you cannot easily see ... water?
- How can you work with experts to achieve consensus?

By and large, the research team did follow the approach outlined above. However, before the site visit stage, the research team met with operations and engineering personnel in the Rock Island District to review the project and to receive

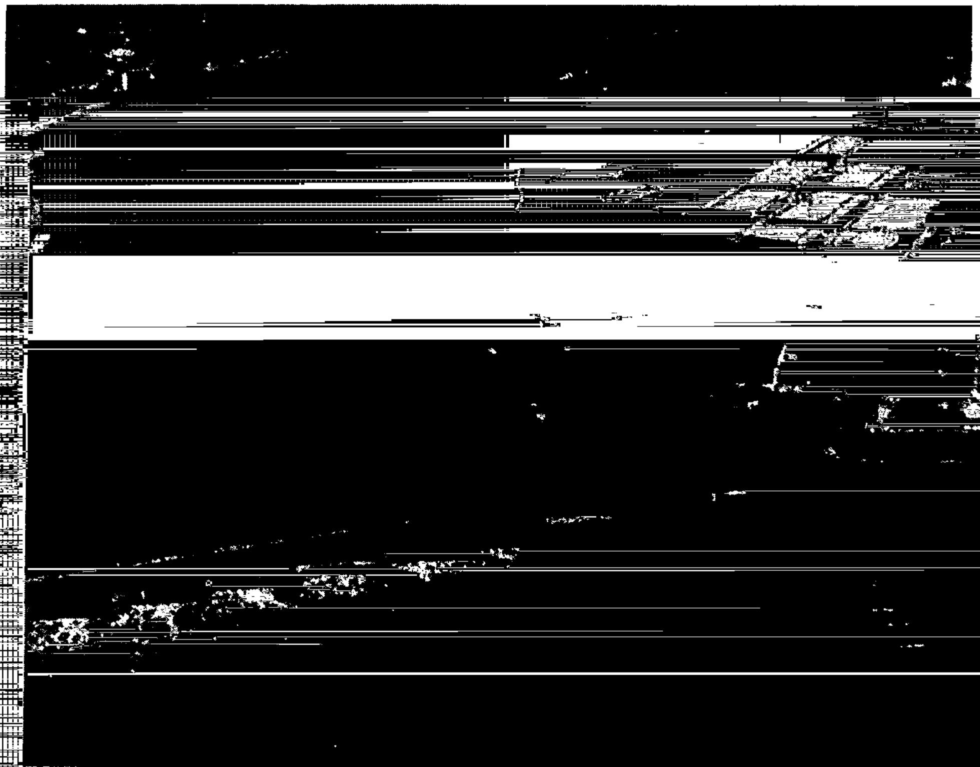

FIG. 1. Mississippi River Locks and Dam #15, Rock Island, Ill.

of these districts that local maintenance inspections were looked at quite differently. For example, in the Nashville District, where all locks exceed 50 ft of hydraulic lift, tolerances for many distresses were quite small. On the other hand, tolerances for distresses in the low lift locks in Rock Island were not thought to be quite as critical. To account for these differences, it became clear that in many of the distresses, the X_{max} value in (1) would have to be somewhat adjustable. In response, the X_{max} limiting values were determined for low lift and for high lift districts and a linearly varying scaling factor was established as a function of the height to width ratio of the gate.

Soon, a consensus of distresses, problems, causes, and measurements began to develop. Of these problems and distresses, the experts identified a list of 10 that seemed most important. Specific distresses included anchorage movement, elevation change, miter offset, gaps, downstream movement, cracks, leaks and boils, dents, noise, jumping or vibration, and corrosion (Greimann et al. 1991). After the experts decided on the distress list, the measurement techniques associated with these distresses were refined and developed. The system was then field tested and calibrated based on analytical algorithms and expert opinions. The algorithms, to the best of everybody's ability, contained all the information gleaned throughout the preliminary investigation process. It was at this time that the weighting factors listed in (2) were developed. Field tests were performed at the lower gates at Keokuk, Iowa in the Rock Island District and at the upper and lower gates at Kentucky and Barclay locks in the Nashville District. These gates were chosen because they fit the profiles of a low and high gate height-to-width ratio, respectively.

The calibration was performed for each of the distresses as well as for the overall gate rating. Overall, the research team was pleased with the system in that the proposed algorithm correlated quite well with the average of the five chosen experts. In some cases, modifications needed to be performed on the system as a result of the calibration results. The research team then revisited the expert panel and modified the system accordingly taking into account the field test-calibration study.

As in the SSP system, two condition indexes were developed based on safety and serviceability. The functional condition index, was based on the previously mentioned 10 distresses while the structural condition index was based on a structural analysis program call CMINV that was developed by the USACE. Rens (1989) provides a detailed description on the CMINV computer program. This structural analysis program went through several load cases associated with the gate in fully loaded, unloaded, and operational modes. Because the structural condition index basically only performed an analysis of the as-built gate according to the current steel code, the structural CI was later replaced by an optional factor of safety calculation utilizing the CMINV program.

In the early stages of the miter-gate CI development, it became clear that when inspected, miter gates possessed a unique quality not many structures share: the miter gate structure experiences significantly varying load states depending on its open or closed position and the head placed upon it. This held many advantages for several of the distresses associated with the program, such as anchorage movement, downstream movement, and elevation change, and helped these distresses evolve into rules and measurements that had good physical meaning. This was especially true in the distress such as anchorage movement, which was the major connection of the gate to the concrete monolith wall. This connection could be loaded into tension and compression and any wear or deterioration could be easily measured.

Early measurement devices were quite crude, such as tape measures and wood pegs. The wood pegs would be driven into the center point of the gate's hinge pin that usually contained a tapped hole in the center. In measuring hinge wear, a U-ring was placed around the wood peg and a tape was stretched tight from it to a fixed location on the anchorage bars. This measurement was then taken while the chamber was full, partially full, empty, etc., with the most important measurement being the difference between a full chamber and a nearly empty chamber.

Over the next five years, this measurement would undergo several evolution cycles to increase the accuracy associated a set of upper and lower miter gate including the gate operating equipment, the concrete in a 600 × 110 ft lock chamber, and a navigation dam with approximately 10 gate bays. It also considers travel and per diem but does not account for overtime labor.) Some districts are literally operating in "breakdown" mode, i.e., they fix what breaks and do not have the need or time for inspection procedures to tell them when something is broken. This perplexing dilemma may be resolved by using CIs, because after successful implementation districts would then be enabled to better define what their true O&M needs are. Another problem is that each District has different drivers for its O&M budgets. These differences are generally due to the different missions tasked to each district and also to the way in which Congress authorized individual district projects. One project in district A may be a small harbor on Lake Michigan, while one project for district B may be a portion of the Mississippi River with several locks and dams. A strategy on how to address Corps-generic and Corps-nongeneric issues within the budget process is a current and ongoing R&D project within the ERDC. Other current R&D efforts are focusing on reducing the required resources while retaining meaningful data. In any case, the systems as they exist today shall require lesser resources once the learning curve is worked through. Immediate benefits have made themselves apparent in anecdotal stories reported by the users, some of which have already been related here. Also, the systematic approach to inspections and the establishment of benchmarks with which to compare structures' O&M profiles is clearly understood by all.

The CI systems are nearly complete in their componentwise development. A lot of work needs to be done in getting the systems used consistently within the USACE. A good bulk of the work will be aimed at linking the CIs and data with other systems for decision support where condition plays an important role. In order to sustain Corps-wide deployment, the system will need support in the form of software, Web-based data housing, and tech support in the form of hotlines and training services. The CI systems are a developed tool with many applications, and the program is now at a pivotal crossroad in the bigger picture of developing decision support for funding activities in the higher managerial levels of the Corps of Engineers.

As this article goes to press, more and more districts have been calling the ERDC for support in condition index implementation. A proposal is currently awaiting Congressional approval for fiscal year 2000 funds to join the CI methodology with risk and reliability assessments; this, coupled with forecasts of economic returns and waterways user benefits derived from O&M investments, can ultimately be used to demonstrate [illegible] for Congress what the actual needs are to properly fund the USACE O&M program. In turn, the districts are historically [illegible] what they received the previous year with [illegible] for nondeferrable maintenance and inflation [illegible] they cannot receive funds based on their actual need.

CONCLUSIONS

The U.S. Army Corps of Engineers is working toward a standard for condition assessment of its civil works. Uniform and consistent condition assessment procedures produce numeric condition indicators called Condition Indices. As a part of standard operating procedure, Condition Indices are required from all Corps district offices in their O&M budget request. The indexes and underlying data serve the districts by establishing an engineering baseline to quantify condition and track trends in condition; they serve headquarters-level managers by ensuring that consistent definitions of condition are being used Corps-wide. The indices are helpful in developing input for other decision support schemes that measure the economic impact of performing particular M&R actions. The CIs established under this R&D are ready to be implemented by comprehensive maintenance management systems, yet there is a lot of work to do. The foundation for decision support systems using structural condition data as variables has been laid for many structures in the Corps' Civil Works Directorate.

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