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Condition rating procedures for lock and dam operating equipment

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Condition rating procedures for lock and dam operating equipment

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

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Department: Civil and Construction Engineering

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Major Professor: Lowell Greimann

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Graduate College
Iowa State University

This is to certify that the Master's thesis of

Scott Michael Mellema

has met the thesis requirements of Iowa State University

Signatures redacted for privacy.

Dedicated to my wife Heather and my parents Harold and Glenda Mellema.

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PREFACE

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Operations Management problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Civil Works Research unit 32280, "Development of Uniform Evaluation for Procedures/Condition Index for Deteriorated Structures and Equipment," for which Stuart Foltz is the Principal Investigator.

The U.S. Army Corps of Engineers established the REMR program to focus more attention on deterioration rates of civil works structures. A team at Iowa State University has focused on the objective to develop an inspection and rating system that uniformly and consistently describes the current condition of the equipment that operates locks, dams, and valve structures.

This study was performed by the Department of Civil and Construction Engineering, Iowa State University, under contract to the U.S. Army Construction Engineering Research Laboratories (USACERL). Principal Investigators for Iowa State University were Lowell Greimann, Jim Stecker, and Scott Mellema. Additional work for this project was performed by Kevin Rens, Tim Kraal, and Tim Meyer.

The objective was achieved by conducting site visits and field investigations with experts from the U.S. Army Corps of Engineers and by using the experts' opinions to develop the rules which form the basis of the rating system.

The following document provides a general description of the inspection and rating

system which includes the definition of a condition index and a description of operating equipment distresses. This is followed by a description of the inspection procedure and the rules for calculating condition indexes for operating equipment.

The material presented in this Master of Science thesis is similar to the report submitted to the Army Corps of Engineers. The work presented in this thesis was developed by the author following discussion with Corps personnel, field inspections and tests, and research of related literature. The author was responsible for the operating equipment component descriptions, the formulation of the inspection forms, and development and calibration of the rating rules (found in Chapters 4 through 12).

CHAPTER 1. INTRODUCTION

General Background

America's aging infrastructure is deteriorating rapidly as many of existing civil works structures near the end of their design life. The deterioration and decay is occurring on water systems, airport runways, subway tunnels, streets, bridges, locks, and dams. Of the roughly 600,000 bridges in the U.S., nearly 45 percent of them are classified as deficient and in need of rehabilitation or replacement [1]. Approximately 9000 state, local, or private dams are "potential risks to public safety"[2] and 54 of 56 locks on U.S. rivers will be in need of major rehabilitation by the year 2000 [3]. Nearly one-third of state officials participating in a recent study said that "one or more of their infrastructure systems pose a serious threat to the health and safety of their citizens" [3].

As the infrastructure systems become more deteriorated, the demand for new construction of civil works projects is overridden by the need to maintain existing projects. In response to this need, many evaluation systems have been developed to regulate the condition of various types of civil works structures. One such evaluation system (Pavement Condition Index) was developed by the Army Corps of Engineers for the U.S. Air Force in order to inventory and regulate the condition of runways [4]. Similar systems developed to rate paved surfaces (streets and runways) have been developed by the city of Chesterfield, Missouri [5], the Port Authority of New York and New Jersey, the American Public Works Association [6], and many others.

Condition rating systems have also recently been established for bridges [7,8]. The Federal Highway Administration (FHWA) has defined a numeric condition rating in the

Recording and Coding Guide in an effort to standardize the ratings [9]. State and federal agencies have cooperated to develop two major bridge management systems, PONTIS and BRIDGEIT, to better monitor the deterioration of bridges. The California Department of Transportation (CALTRANS), under an agreement with the Federal Highway Administration (FHWA), developed the PONTIS program [10]. The second major program, BRIDGEIT, is being developed by a private consulting firm through the National Cooperative Highway Research Program (NCHRP).

The objectives of the condition rating systems are roughly the same: to monitor the deterioration of the structures in order to prioritize the rehabilitation and repairs, and to do so in a standardized method. This monitoring is accomplished with periodic inspection and condition assessment. The conditions of the structures are determined by observing or measuring the severity of distresses. These distresses range from cracks, potholes, joint spalls, and patching [4,5] in pavement condition assessment to deteriorated railing, damaged curb, and corrosion of reinforcing steel in the condition assessment of bridges [7].

REMR Background

The U.S. Army Corps of Engineers (USACE) is directly responsible for the operation and safety of approximately 600 hydraulic structures (lock chambers, flood control dams, powerplants, etc. [11]. As the structures age (49% are over 30 years old), a greater emphasis is being placed on the repair and rehabilitation of these structures. In 1984 the USACE established the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program. REMR was designed to focus attention on maintenance and to record and build baseline data to monitor deterioration rates of these structures in an effort to extend the service life of

existing structures.

REMR is a research program involved in the development of inspection procedures for dams [12], rubble breakwaters and jetties [13], railroad track networks [14,15], concrete navigation lock monoliths [16,17], etc. An Iowa State University (ISU) project team, working in conjunction with the REMR program, has been involved in the development of inspection and rating procedures for several civil works structures including steel sheet pile [18], miter lock gate [19], sector gate [20], tainter and butterfly valves [21], and tainter dam and lock gates [22].

Equipment used to operate lock, valve, and dam structures, which include assemblies such as: exposed gear assemblies, enclosed gear assemblies, gear rack assemblies, strut arm assemblies, rocker arm assemblies, cable assemblies, chain assemblies, hydraulic cylinder assemblies, and coupling assemblies are addressed in this thesis. Not included in this evaluation of operating equipment are hydraulic motors, hydraulic pumps, hydraulic hoses, hydraulic valves, limit switches, brakes, electric wiring, and electric motors.

Objective

An Iowa State University research team, applying the REMR project objectives to lock and dam operating equipment, has developed an inspection program to detect problems in operating equipment at an early stage. The objective of this project is to develop an inspection and rating procedure to describe the overall condition of operating equipment assemblies accurately. Such a rating will also flag a potential problem for the engineer.

CHAPTER 2. INSPECTION AND RATING PROCESS

Overview

The concepts and ideas presented here for the maintenance management of operating equipment rely heavily on work in similar projects for steel sheet pile structures, miter lock gate structures, sector gate structures, tainter and butterfly valves, and tainter dam and lock gates. During that earlier work, basic ideas such as structural considerations, condition indexes, safety and serviceability, quantification of distresses by field measurements, limiting values of distresses, and others began to evolve. As these concepts were applied to lock and dam operating equipment, several enhancements and some new ideas have become apparent.

During the course of this project, the ISU team has met with Corps personnel and conducted site visits and field investigations at many lock and dam facilities. These meetings led to the identification of several basic considerations for operating equipment. Corps experts conveyed their opinions as to the critical components of lock and dam operating equipment, suggested means of quantifying the condition of these components, and related them to the overall condition of the operating equipment assemblies. The project team then took the experts' comments and formulated them into an inspection procedure and a tentative set of rating rules. Field tests of the inspection form and rating rules were conducted at 16 lock and dam facilities. At each test site, improvements to the rules and inspection process were suggested by the experts. Insofar as possible, the suggestions have been incorporated into this work except for cases of conflicting expert opinion. Software will be written to store the inspection data and calculate the condition rating.

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Inspection and Rating Procedure

The inspection and rating procedure is illustrated schematically in Fig. 1. The entire process is based on a field inspection of the operating equipment.

Field Inspection Procedure

Simplicity and adaptability form the basis of the inspection procedure. Conforming to these guidelines, the inspection program had to be applicable to a wide variety of operating equipment and, yet, relatively straightforward for Corps personnel to implement in the field.

For rating systems previously developed by the ISU project team, the field inspection was based on data that was easily obtainable. All data were measured with a tape measure, a level, a ruler, dial gauges, or by subjective observation (poor, average, good, excellent, etc.). The procedure was kept as simple as possible, while still obtaining quantitative and applicable information to assess the structure. The lock and dam may remain in an operating mode during the procedure. In general, the level of inspection for operating equipment is at a somewhat lower level of inspection than for previously inspected structures, i.e., dam gates. Hence, some of the rules involve more subjective questions to quantify the condition.

In addition to simplicity, the other goal was to develop a general inspection procedure that was adaptable to many different types of operating equipment. The operating equipment covered in this report include lock, valve, and dam operating equipment. Within each of these structures, there are numerous designs and combinations of assemblies. For example, dam gates can be operated by various combinations of exposed gears, enclosed gears, gear racks, struts, cables, chains, hydraulic cylinders, and couplings. To accommodate these variations, separate inspection forms were developed for each assembly that make up the operating

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┌─────────────────────────┐
│     Field Inspection    │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│       Data Entry        │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│      Expert Rules       │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│     Condition Index     │
└─────────────────────────┘
             │
      ┌──────┴──────┐
      ▼             ▼
┌──────────────┐ ┌──────────────┐
│   Report     │ │  Structural  │
│ Generation   │ │    Notes     │
└──────────────┘ └──────────────┘
```
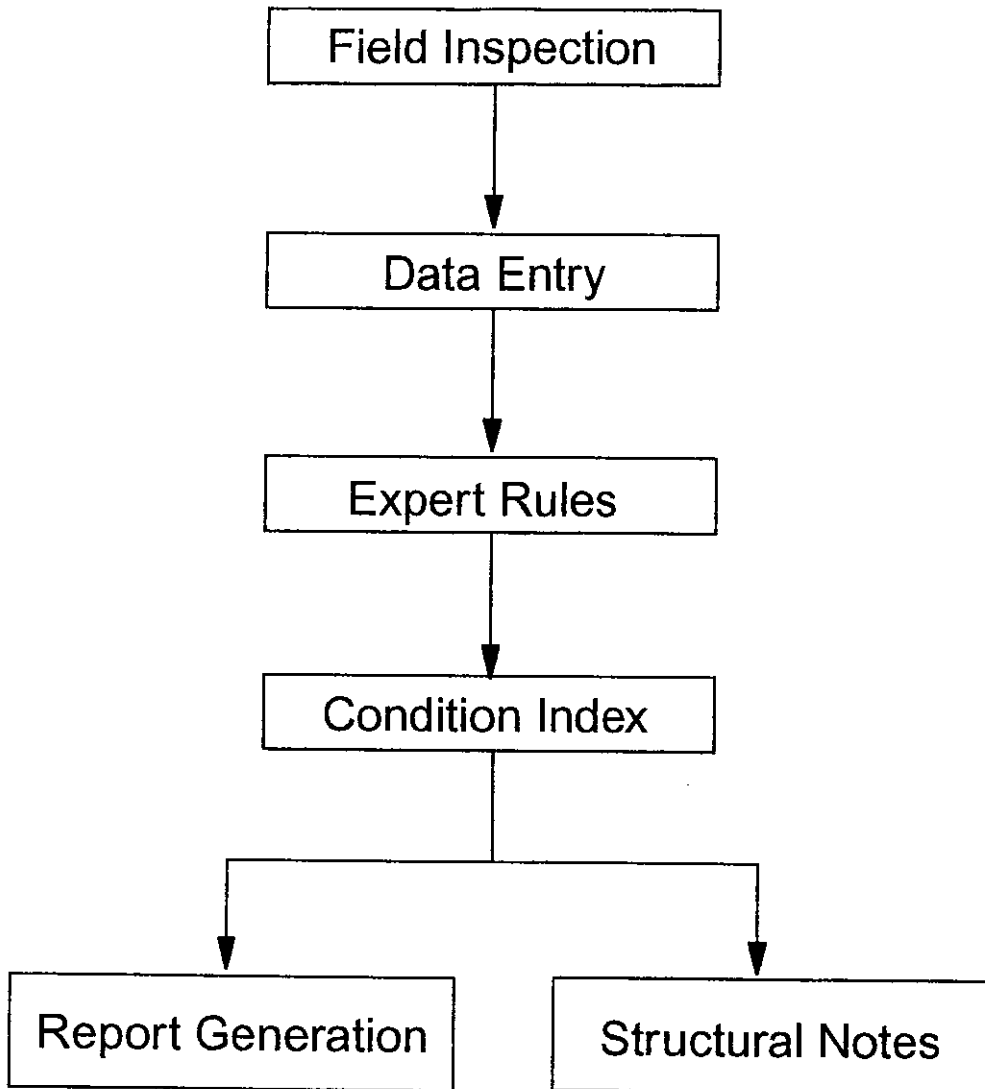
Figure 1. Inspection and Rating Procedure

equipment.

Inspection Form

The inspection forms for lock gate, valve, and dam gate operating equipment were designed to provide flexibility in documenting a variety of field conditions. The first two pages of the form address location of the equipment, historical information, inspection and maintenance history, and the current operating characteristics. These pages should be completed before the field inspection. Pages beyond the first two provide space for entering field measurements such as anchorage movements, cracks, and corrosion and should be completed in the field. These measurements are used directly to rate the condition of the operating equipment. The following paragraphs briefly outline the inspection form.

General Information: General information related to the structure is recorded on Pages 1 and 2 of the inspection form, which are shown and described in detail in Chapter 3. Separate Page 1 and 2 sets were developed for the operating equipment for: (1) lock structures, (2) valve structures, and (3) dam structures. Recorded information includes project reference data to identify and locate the specific structure. Further questions categorize the structure into a particular type and function. In particular, the path of power transfer is itemized on Page 1. The flow of power constitutes the basis for which inspection forms will be used to inspect the condition of the operating equipment assemblies within the structure. Historical descriptions of maintenance, modifications, and inspections are recorded on Page 2 for reference only.

Field Measurements: The remaining pages of the inspection form are used to describe the condition of each assembly which makes up the operating equipment. The

inspection forms which describe the condition of each assembly consist of one to three pages

which are identified as Parts 1, 2, and 3. The complete inspection form set for a structure

will consist of one Page 1 and one Page 2 and a number of pages to describe the condition of

the assemblies, depending on the type and number of assemblies in the operating equipment.

Separate sets of inspection forms exist for each of the nine assemblies listed in Table 1.

Several simple measurements and observations concerning problems or distresses in each

assembly are recorded. The inspection forms corresponding to the separate assemblies can be

found in Chapters 4 through 12.

Condition Index

The field observations are used in the expert rules to determine the condition index

(CI) for each operating equipment assembly. A condition index is the numerical measure used

Table 1. List of Operating Equipment Assemblies

Assembly	Inspection and Rating Procedure
Exposed Gear	Chapter 4
Enclosed Gear	Chapter 5
Rack	Chapter 6
Strut Arm	Chapter 7
Rocker Arm	Chapter 8
Cable	Chapter 9
Chain	Chapter 10
Hydraulic Cylinder	Chapter 11
Coupling	Chapter 12

to rate the current state of the operating equipment. The purpose of the CI is twofold. First, the CI values serve as a planning tool meant to focus management attention on operating equipment most likely to warrant immediate repair or further evaluation. Second, the CI values can be used to monitor changes in the general condition over time and can serve as an approximate comparison of the condition of operating equipment at different locations.

A common definition of CI was developed during previous Repair, Evaluation, Maintenance, and Rehabilitation (REMR) work done by the ISU project team (Table 2). The REMR CI is a numerical scale, ranging from a low of 0 to a high of 100. The numbers indicate the relative need to perform REMR work because of deteriorating characteristics of the operating equipment. For management purposes, the CI scale is also calibrated to group

Table 2. Condition Index Scale

Value	Condition Description
85-100	Excellent: No noticeable defects. Some aging or wear may be visible.
70-84	Good: Only minor deterioration or defects are evident.
55-69	Fair: Some deterioration or defects are evident, but function is not significantly affected.
40-54	Marginal: Moderate deterioration. Function is still adequate.
25-39	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.
10-24	Very Poor: Extensive deterioration. Barely functional.
0-9	Failed: No longer functional. General failure or complete failure of a major structural component.

operating equipment into three basic categories or zones, as listed in Table 3. If a structure is

designed and constructed properly, it has an initial CI of 100. As time passes and the

structure is exposed to varying environmental and operational situations, its condition will

deteriorate. The CI will degrade as various distresses are incurred.

Table 3. Condition Index Zones

Zone	CI Range	Action
1	70-100	Immediate action not required.
2	40-69	Economic analysis of repair alternatives recommended to determine appropriate maintenance action.
3	0-39	Detailed evaluation required to determine the need for repair, rehabilitation or reconstruction. Safety evaluation is recommended.

Because the CI involves engineering judgment and depends on the experience of the

person making the evaluation, some aspects of the CI were difficult to capture. Experts in the

area of operating equipment were interviewed and discussion continued until a consensus

began to develop. The authors have attempted to blend all the opinions expressed at these

meetings into a set of "expert opinion" rules that are embedded in the evaluation that

constitutes the CI. The rules have been designed to interpret straightforward, visual

observation data in much the same manner that a seasoned engineer would interpret field

observations.

Two general structural criteria for evaluating the CI are available: safety and

serviceability. Safety relates to the performance of a structure beyond normal service

conditions, for example, under such abnormal conditions as excessive load. It relates to the probability of failure. Serviceability relates to the performance of operating equipment under normal service conditions, for example, hydraulic cylinder drift. The CI for each distress includes both safety and serviceability aspects. Compared to other structural components at a lock and dam facility few safety aspects are associated with operating equipment.

A series of critical measurements and observations are made on each operating equipment assembly to quantify the CI. Experts were asked to interpret these measurements in light of the serviceability and safety of the operating equipment and to assign the limiting values to the measurements.

Distress CI: The assemblies in this project each have between five and fifteen distresses which affect the assembly condition index. Each of these distresses can detract from the safety and the serviceability of that assembly. Tables 4 through 12 contain a brief description of the distresses for each of the nine assemblies listed in Table 1. Many distresses are quantified by a measurement X. For example, hydraulic cylinder drift is a distress quantified by the motion of the cylinder rod

when the oil valves are closed. In this case the CI is calculated by

$$CI = 100(0.4)^{\frac{X}{X_{MAX}}} \qquad (2.1)$$

where X_{MAX} is some limiting value of X. Figure 2 illustrates the equation and the previously mentioned zones (Table 3). Experts have selected X_{MAX} to be the point at which the operating equipment requires immediate repair or at least a more detailed inspection and CI evaluation.

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Table 4. Exposed Gear Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Anchorage movement, deterioration	Movement of embedded anchorage system and damaged components
Bearing/bushing wear	Excessive play in the exposed reduction gear bearing or bushing
Roller support wear/damage	Freezing or wear of the roller bearings or bushings
Cracks	Breaks in the steel components
Tooth wear	Wearing of the gear teeth
Reduced tooth contact	Improper engagement of the teeth
Damaged teeth	Chipped, deformed, pitted, gouged, or corroded teeth

Table 5. Enclosed Gear Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Anchorage movement, deterioration	Movement of embedded anchorage system and damaged components
Cracks	Breaks in the steel components
Damaged teeth	Chipped, deformed, pitted, gouged, or corroded teeth
Temperature rise of gear box	Temperature change in the gear box oil
Oil leakage	Leakage of oil
Oil contamination	Contamination of oil

Table 6. Gear Rack Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Cracks	Breaks in the steel components
Rack attachment deterioration	Deterioration of bolts which anchor the rack to the gate
Reaction roller wear/damage	Wear and freezing of reaction roller bearings and bushings
Reaction roller anchorage movement /deterioration	Movement of embedded anchorage system and damaged components
Gear/rack displacement	Relative displacement between the gear and rack perpendicular to the rack
Rack wear	Edge and bottom wear of the rack
Tooth wear	Wearing of the gear teeth
Reduced tooth contact	Improper engagement of the teeth
Damaged teeth	Chipped, deformed, pitted, gouged, or corroded teeth

Table 7. Strut Arm Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Strut connection movement	Displacement between pin and bushing
Compression spring movement	Abnormal functioning of the compression spring
Corrosion	Loss of steel due to interaction with the environment
Cracks	Breaks in the steel components

Table 8. Rocker Arm Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Rocker and connecting rod connection movement	Movement between the rocker arm and the connecting rod
Pivot point anchorage movement /deterioration	Movement of embedded anchorage system and damaged components
Pivot point pin movement	Movement between the rocker arm the pivot point anchorage system
Corrosion	Loss of steel due to interaction with the environment
Cracks	Breaks in the steel components

Table 9. Cable Assembly Distresses

Distress	Brief Description
Noise, jump, and vibration	Abnormal noise, jumping, or vibration during operation
Outer wire wear	Reduction in the diameter of the cable wires
Reduction in rope diameter	A reduced rope diameter
Corrosion	Loss of steel due to interaction with the environment
Bird cages, kinks, and protruding core	Deformation of the rope by either bird cages, kinks in the rope, or a core which is protruding from the rope
Unlayed strands	Cable strands which are unlayed
Wire breakage	The number of broken wires in any one cable lay
Unequal tension	Improper cable tension
Drum wear	Wear on cable guides and drum groove
Drum anchorage movement/deterioration	Movement of embedded anchorage system and damaged components
Sheave wear	Wear on the sheave groove
Sheave bearing/bushing wear	Excessive play in the sheave bearing or bushing
Sheave anchorage movement/deterioration	Movement of embedded anchorage system and damaged components
Idler/roller wear	Improper operation of idlers and rollers
Gate or valve connection movement	Relative movement at the connection between the cable and the lifting bracket

Table 10. Chain Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Linkage wear/elongation	Wear and elongation of the chain links, pins, and bearings
Cracks	Breaks in the steel components
Frozen links	Links will not rotate or displace relative to each other
Corrosion	Loss of steel due to interaction with the environment
Sprocket anchorage movement/deterioration	Movement of embedded anchorage system and damaged components
Sprocket wear	Wear of the sprocket
Gate connection movement	Relative movement between the chain and the lifting bracket

Table 11. Hydraulic Cylinder Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Anchorage movement, deterioration	Movement of embedded anchorage system and damaged components
Rod end connection movement	Relative movement between the hydraulic rod and the strut
Corrosion/pitting of rod	Corrosion and possibly pitting of hydraulic rod due to interaction with the environment
Damage of rod	Scoring, nicking, or other damage on the rod
Oil leakage	Leakage of oil from the rod end of the hydraulic cylinder
Drift	Movement of hydraulic rod with respect to the cylinder with load
Damaged guide	Corrosion and/or attachment movement of the guides

Table 12. Coupling Assembly Distresses

Distress	Brief Description
Noise, jump, vibration	Abnormal noise, jumping, or vibration during operation
Cracks	Breaks in the steel components
Corrosion	Loss of steel due to interaction with the environment
Input shaft and hub movement	Relative movement between the input shaft and the hub
Output shaft and hub movement	Relative movement between the output shaft and the hub
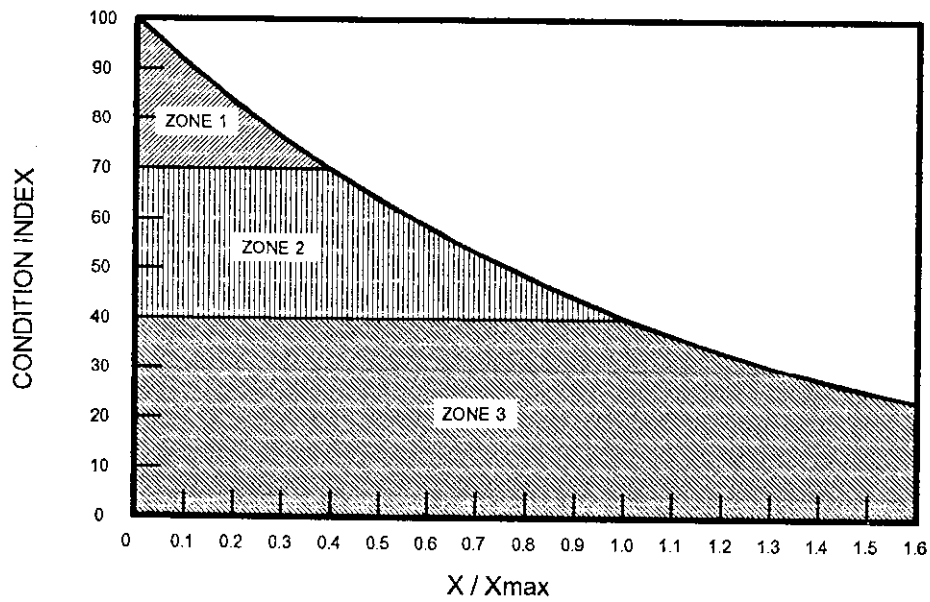
Figure 2. Condition Index Related to X/X_{MAX}

In other words, it corresponds to a CI of 40 and is a potentially hazardous situation.

In Chapters 4 through 12, the definition and measurement of X and X_{MAX} values are described for each assembly. Illustrated examples and potential causes of each distress which must be addressed in the maintenance and repair of the operating equipment are also included. Diagnosing causes for each distress is a complex issue. Many times a distress may have several possible causes, and often a combination of distresses must be present before a certain cause can be identified.

Assembly CI: The calculation of the assembly CI is also a complicated task. Although all of the individual CI_is (where i refers to an individual distress) contribute to the assembly CI, some are more significant in evaluating the overall condition of the assembly. To account for this varying significance, weighting factors, w_i, were obtained for each individual CI_i. Weighting factors were obtained by averaging the subjective weighting factors given by five operating equipment experts from the Corps of Engineers: Fred Joers (Rock Island District), Jim Bartek (Rock Island District), Allen Matherne (New Orleans District), Ross Woodbury (Louisville District), and Joe Britton (Jacksonville District).

Before the weighting factors were established by the experts, a letter and rating form were sent to each expert which asked the experts to identify the importance of each distress and to determine whether it should be considered critical to the structural stability of the assembly or whether it should be considered noncritical. A critical distress is a very important distress, the CI of which can control the assembly CI. The assembly CI is the minimum of the CI for the critical distresses and weighted average of all the noncritical distresses.

$$CI = \text{Minimum } \{CI_j(s) , Ci_w\} \qquad (2.2)$$

where CI_js are the CIs of the critical distresses (j refers to critical distresses) and CI_w is the weighted average of the noncritical distresses, as discussed in the following paragraph. Eight of the nine assemblies have at least one distress which is considered critical. None of the distresses are critical in the hydraulic cylinder assembly.

After analyzing the responses to the first letter, a second letter and rating form were then sent out to the experts, this time asking for the relative weights, w_i, of each distress which they considered noncritical. The weighting factors were normalized with the following equation

$$W_i = \frac{w_i}{\Sigma w_i}(100) \tag{2.3}$$

such that

$$\Sigma W_i = 100 \tag{2.4}$$

The experts' average weighting factors and the normalized weighting factors are listed in Tables 13 through 22 for each of the nine assemblies with the exception of the gear rack assembly for which there are two tables (one for the sector gate application and one for the other gear rack applications). The normalized weighting factors are used to calculate the weighted average CI_w for the noncritical distresses

$$CI_w = W_1 CI_1 + W_2 CI_2 + \ldots + W_n CI_n \tag{2.5}$$

where n is the number of non-critical distresses for that assembly.

During field testing, it became clear that as a distress became more severe, its relative

Table 13. Weighting Factors for the Exposed Gear Assembly

Distress	W_i
Noise, jump, and vibration	27.5
Anchorage movement/deterioration	26.8
Bearing/bushing wear	12.3
Roller supports wear/damage*	7.0
Cracks	critical
Tooth wear	2.6
Reduced tooth contact	9.0
Damaged teeth	14.8

* If not applicable, w_i for this distress is zero.

Table 14. Weighting Factors for the Enclosed Gear Assembly

Distress	W_i
Noise, jump, and vibration	24.1
Anchorage movement/deterioration	21.5
Cracks**	critical
Damaged teeth**	23.3
Temperature rise of gear box	17.2
Oil leakage	2.3
Oil contamination	11.6

** If not observable, w_i for this distress is zero.

Table 15. Weighting Factors for the Gear Rack Assembly (Sector Gate Racks)

Distress	W_i
Noise, jump, and vibration	34.3
Cracks	critical
Rack attachment deterioration	25.1
Tooth wear	6.4
Reduced tooth contact	14.3
Damaged teeth	19.9

Table 16. Weighting Factors for the Gear Rack Assembly (Other Applications)

Distress	W_i
Noise, jump, and vibration	29.0
Cracks	critical
Reaction roller wear/damage	10.2
Reaction rollers anchorage movement/deterioration	15.4
Gear/rack displacement	9.0
Rack wear	3.2
Tooth wear	4.9
Reduced tooth contact	11.4
Damaged teeth	16.9

Table 17. Weighting Factors for the Strut Arm Assembly

Distress	W_i
Noise, jump, and vibration	44.5
Strut connection movement	20.6
Compression spring movement	27.7
Corrosion	7.2
Cracks	critical

Table 18. Weighting Factors for the Rocker Arm Assembly

Distress	W_i
Noise, jump, and vibration	27.7
Rocker and connecting rod connection movement	19.3
Pivot point anchorage movement/deterioration	38.9
Pivot point pin movement	4.9
Corrosion	9.2
Cracks	critical

Table 19. Weighting Factors for the Cable Assembly

Distress	W_i
Noise, jump, and vibration	9.1
Outer wire wear	7.5
Reduction in rope diameter	14.1
Corrosion	8.8
Bird cages, kinks, and protruding core	critical
Unlayed strands	10.5
Wire breakage	critical
Unequal tension	7.0
Drum wear	1.3
Drum anchorage movement/deterioration	10.6
Sheave wear*	2.7
Sheave bearing/bushing wear*	4.1
Sheave anchorage movement/deterioration*	10.6
Idlers/rollers wear*	3.4
Gate or valve connection movement**	10.5

* If not applicable, w_i for this distress is zero.
** If not observable, w_i for this distress is zero.

Table 20. Weighting Factors for the Chain Assembly

Distress	W_i
Noise, jump, and vibration	16.3
Linkage wear/elongation	12.3
Cracks	critical
Frozen links	23.6
Corrosion/pitting	9.7
Sprocket anchorage movement/deterioration	21.8
Sprocket wear	2.9
Gate connection movement**	13.4

** If not observable, w_i for this distress is zero.

Table 21. Weighting Factors for the Hydraulic Cylinder Assembly

Distress	W_i
Noise, jump, and vibration	18.1
Anchorage movement/deterioration	21.0
Rod end connection movement	13.1
Corrosion/pitting of rod	12.3
Damage of rod	14.8
Oil leakage	7.4
Drift	11.2
Damaged guide*	2.1

* If not applicable, w_i for this distress is zero.

Table 22. Weighting Factors for the Coupling Assembly

Distress	W_i
Noise, jump, and vibration	89.3
Cracks	critical
Corrosion	10.7
Input shaft and hub movement	critical
Output shaft and hub movement	critical

importance became larger. In other words, as the CI_i of an individual distress approaches Zone 3, it becomes more significant in the calculation of the weighted CI_w. In previous Iowa State project work[20,21,22], an adjustment factor (AF) was applied to the weighting factors of distresses for which the individual CI_i was less than 70, or in Zone 2 or 3. The adjustment factor has a maximum value of eight when the individual CI_i is in Zone 3, and is obtained by the following linear equation when the individual CI_i is in Zone 2

$$AF_i = 8 - 7 * \frac{(CI_i - 40)}{30} \qquad (2.6)$$

The value of the adjustment factor versus the CI_i is shown graphically in Figure 3.

Field Testing

The performance of the rating rules was evaluated by comparing the calculated CI values based on the rules to the CI values subjectively determined by Corps personnel who are operating equipment experts. Several site visits were conducted and Corps experts were
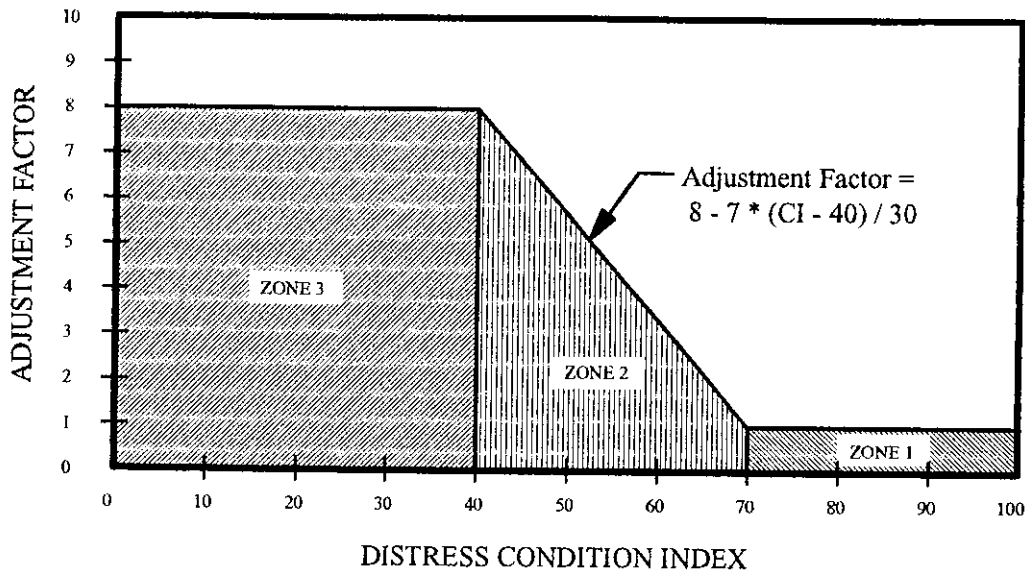
Figure 3. Weight Adjustment Factor

interviewed to establish an initial set of condition index rules. In January 1995, several field tests of operating equipment were performed in the Jacksonville District. The lock and dam sites at which the tests were performed were: (1) W.P. Franklin Lock and Dam, (2) Ortona Lock and Dam, (3) Moore Haven Lock and Dam, and (4) St. Lucie Lock and Dam. The Corps personnel who participated were: Fred Joers (Rock Island District), Jim Bartek (Rock Island District), Allen Matherne (New Orleans District), Ross Woodbury (Louisville District), Joe Britton (Jacksonville District), and Steve Schneider (Jacksonville District). Each expert was asked to rate subjectively the individual distresses for various operating equipment

assemblies, that is to assign a CI to each distress. The experts were also asked to assess a combined assembly CI. After the field test, the inspection procedure and inspection forms were changed significantly following recommendations by the experts.

In March of 1995, field tests were conducted in the Louisville District at several sites: (1) Cannelton Lock and Dam, (2) Green River 1 Lock and Dam, (3) Green River 2 Lock and Dam, and (4) Newburgh Lock and Dam. The participating Corps personnel were Joers, Bartek, Matherne, Woodbury, and Britton. The same calibration procedure was used again to further refine and improve the inspection process, inspection form, and rules.

Bar charts in Chapters 4 through 12 compare the experts' subjective CIs to the calculated individual and the assembly CIs. In each chart the individual bars represent:

- the average of the experts' CI
- the highest expert CI
- the lowest expert CI
- the CI calculated by rating rules

Directly beneath each set of four bars, are three groups of letters and in some cases numbers which identify the assembly from which the bars were produced. The first set of letters identify the lock and dam facility at which the assembly is located. The second set of letters identify the type of structure (lock gate, valve, or dam gate) on which the assembly operates. The final set of letters or numbers identify the particular structure at that site either with a number for dam gates or with a word description (upper right) for lock gates and valves . Tables 23-25 list the abbreviations and their meanings for the three respective groups.

Table 23. Abbreviations for Lock and Dam Facilities

Lock and Dam Facility	Abbreviation
W.P. Franklin	WP
Ortona	O
Moore Haven	M
St. Lucie	SL
Cannelton	C
Green River I	G1
Green River II	G2
Newburgh	N

Table 24. Abbreviations for Structure Types

Structure Type	Abbreviation
Miter Lock Gate	LM
Sector Lock Gate	LS
Tainter Valve	VT
Tainter Dam Gate	DT
Vertical Lift Dam Gate	DV

Table 25. Abbreviations for Structure Identification

Structure Identification	Abbreviation
Upper Right	UR
Lower Right	LR
Upper Left	UL
Lower Left	LL
Number	1, 2, ...

Some distresses were not observed in the tested assemblies during the field testing. In these cases the calculated CI_is were 100 and the experts' average CI_is were at least 90. Therefore, these cases are not presented in the bar charts. An expert adjusted average CI (the average of the experts' CIs excluding the highest and the lowest) was calculated and compared with the experts' average CI. The two averaging methods yielded approximately the same results, therefore, only the average of the experts' CI is shown.

Site visits to several Illinois locks and dams were made in June of 1995. Operating equipment at the following sites was observed: (1) T.J. O'Brien Lock and Dam, (2) Chicago Lock, (3) Lockport Lock and Dam, (4) Brandon Road Lock and Dam, (5) Dresden Island Lock and Dam, (6) Marseilles Lock and Dam, (7) Starved Rock Lock and Dam, and (8) Mississippi River Lock and Dam #16. Fred Joers and Jim Bartek participated in the visits during this week. The inspection procedures for several of the assembly distresses were performed at the above sites. The inspection procedures were examined in an effort to (1) fine tune the procedures, (2) make format changes to the inspection form, and (3) adjust the

CI calculation rules. The visits were beneficial in reformatting the inspection form and finalizing the inspection procedure and rules for some of the distresses.

Layout of Following Chapters

One of the nine operating equipment assemblies listed in Table 1 is described in each of the Chapters 4 through 12. In addition to component identification, these chapters include the inspection forms pertaining to the nine assemblies. The rules for evaluating the individual CI_is and combined assembly CIs with example illustrations showing the calculations of these CI_is are also included. The final section of each of these chapters show the comparison between the CIs calculated from the rules assembled by the ISU project team and the subjective CIs given by the experts for assembly and combined distresses.

CHAPTER 3. INSPECTION FORM: GENERAL INFORMATION

Introduction

This chapter begins with a brief description of lock gates, valves, and dam gates. An overall view of a lock and dam facility is shown in Figure 4 in which various operating equipment areas are highlighted. The pages following the gate and valve descriptions contain inspection forms for: (1) lock gate, (2) valve, and (3) dam gate operating equipment; and illustrations of some of the equipment (Fig. 5-10). The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

Lock Gates

Lock gates can be either miter, sector, tainter, or vertical lift lock gates. Miter gates rotate on hinges which are attached to the concrete monolith wall and resist forces similar to a three-hinged arch. Sector gate structures have skin plates which are sectors of a circle. Sector gates can resist water pressure on either side of the skin plate contrasted to miter gates which can only have net water pressure on the upstream side. Tainter lock gates sometimes serve as upper gates in a lock chamber and are usually submersible. Vertical lift gates are made up of skin plates which are framed with horizontal and vertical girders.

Valves

Valves are used inside the culverts of the filling and emptying systems of lock structures. At least two valves are necessary in each longitudinal culvert. A filling valve is located between the upper pool intake and the chamber intake ports. An emptying valve is located between the chamber outlet ports and the lower pool discharge. There are many valve

types, some of the most common being tainter, vertical lift, and butterfly.

Dam Gates

Dam gates are used at the top of a dam spillway to control the upper pool elevation. Their basic purpose is to hold back and to pass water. The types of dam gates currently used are tainter, vertical lift, and roller.

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FLOW

DAM GATES

DAM
OPERATING
EQUIPMENT

GATE OPERATING
EQUIPMENT

STILLING BASIN

LOCK GATE

VALVE OPERATING
EQUIPMENT

Figure 4. Lock and Dam Schematic

Page 1. Comments: Recordkeeping Data

Completed before the site inspection and verified or changed during the site inspection.

Enter the NAME of the Corps of Engineer Project Title.

Indicate the BODY OF WATER and NEAREST TOWN.

Indicate GATE IDENTIFICATION. Circle the gate which will be inspected and the TYPE of gate. The orientation of the gate, left or right, is determined by looking downstream.

Select ASSEMBLIES that exist in the operating equipment and number them in order of POWER TRANSFER from source of the power to the structure. If the equipment splits into a LEFT and RIGHT set of equipment, place the power transfer number in the columns labeled left and right, respectively. Place an L behind the number if it is on the left side and an R behind the number if it is on the right side. If the assembly is common to (shared by) both sides or if there is no power split, place the numbers in the COMMON column. Left and right are determined when facing downstream.

Example: One Page 1 can be used for the inspection of any combination of assemblies in a lock gate. If the upper right gate leaf is inspected, RIGHT LEAF should be circled in the row labeled UPPER GATE. The gate type should also be indicated by circling the appropriate type. The order of power transfer of the assemblies in the structure should be numbered; for example, in Fig. 6 the order is 1) Hydraulic Cylinder, 2) Rack, 3) Exposed Gear, and 4) Strut. The numbering for this example is shown below.

ASSEMBLY LIST AND ORDER OF POWER TRANSFER

	COMMON	LEFT	RIGHT
Exposed Gear	3		
Enclosed Gear			
Gear Rack	2		
Strut Arm	4		
Rocker Arm			
Cable			
Chain			
Hydraulic Cylinder	1		
Coupling			

The appropriate inspection Parts 1 and 2 for the selected assemblies will then be completed and combined with the Page 1 and 2 for a complete set of inspection forms. If the gate shown in Fig. 6 was inspected, one hydraulic cylinder Parts 1 and 2, one gear rack Parts 1 and 2, one exposed gear Parts 1 and 2, and one strut page must be added to the Page 1 and Page 2 for a complete set.

Page 2 comments: Historical or General Data.

Completed prior to the site inspection and verified or changed during the site inspection.

Operating equipment components are sometimes replaced or removed during rehabilitation. It is important for later reference to record the history of the in-place structure.

Enter major MAINTENANCE, REPAIRS, OR OTHER MODIFICATIONS performed on the operating equipment within the past 10 years.

Enter PREVIOUS INSPECTION information for reference purposes.
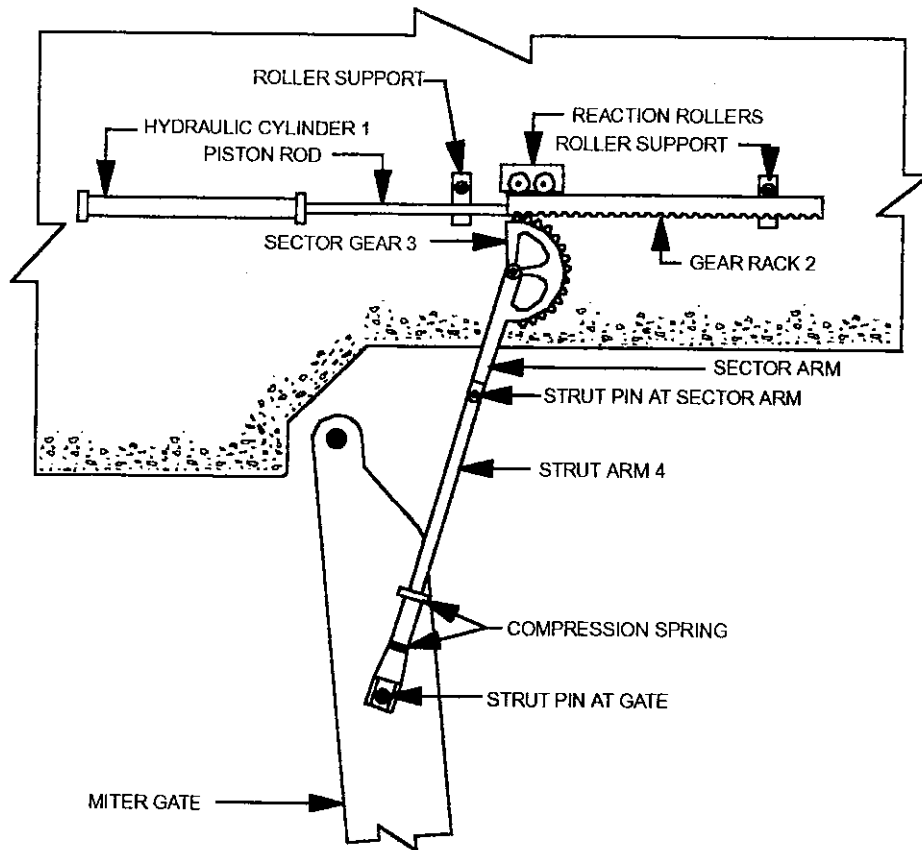
Figure 6. Plan View of Miter Lock Gate Operating Equipment
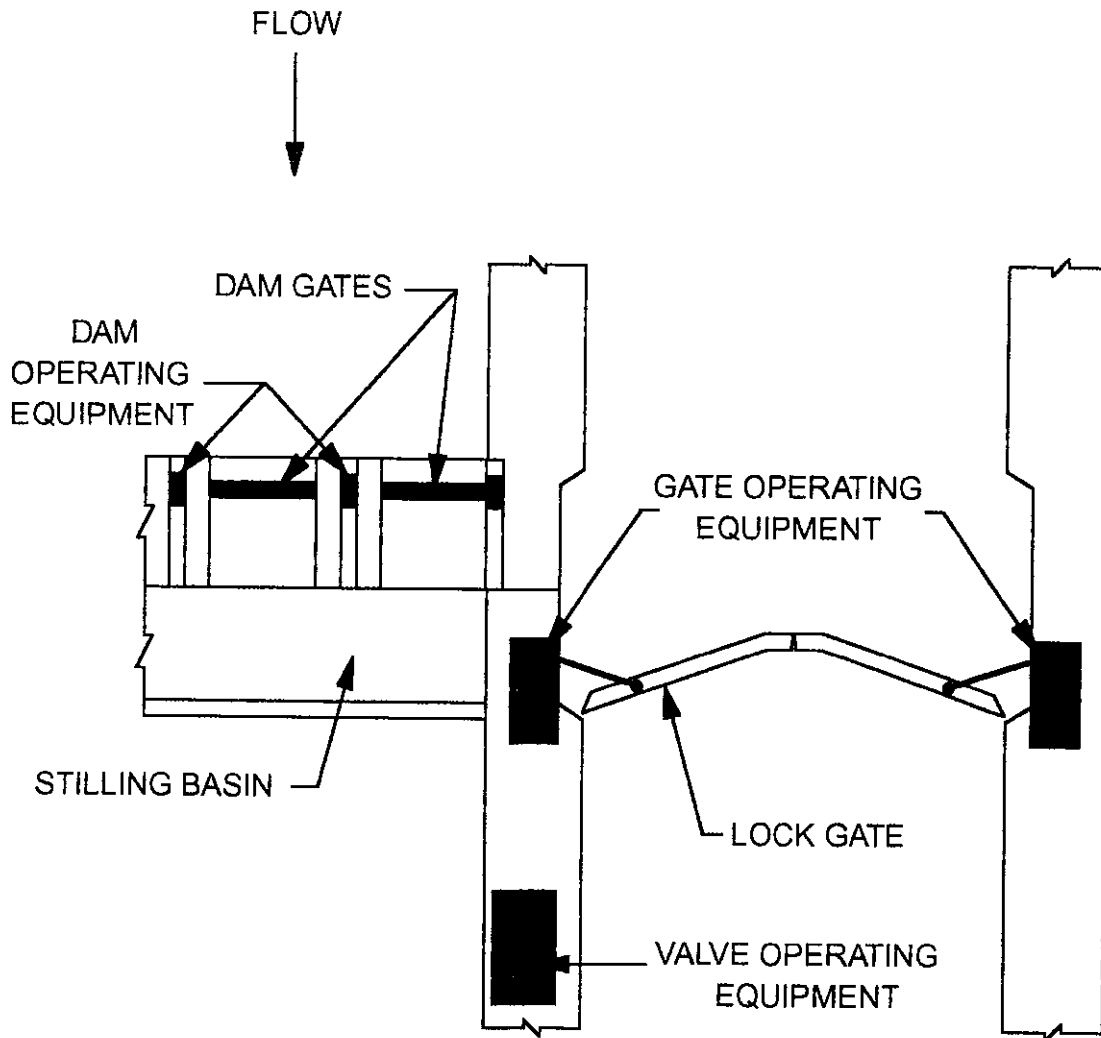
Page 1. Comments: Recordkeeping Data

Completed before the site inspection and verified or changed during the site inspection.

Enter the NAME of the Corps of Engineer Project Title.

Indicate the BODY OF WATER and NEAREST TOWN.

Indicate VALVE IDENTIFICATION. Circle the valve which will be inspected and the TYPE of VALVE. The orientation of the valve, left or right, is determined by looking downstream.

Select ASSEMBLIES that exist in the operating equipment and number them in order of POWER TRANSFER from source of the power to the structure. If the operating equipment splits into a LEFT and RIGHT set of equipment, place the power transfer number in the columns labeled left and right, respectively. Place an L behind the number if it is on the left side and an R behind the number if it is on the right side. If the assembly is common to (shared by) both sides or if there is no power split, place the numbers in the COMMON column. Left and right are determined when facing downstream.

Example: One Page 1 can be used for the inspection of any combination of assemblies in a valve. If the right filling valve is inspected, the RIGHT VALVE of the FILLING VALVE should be circled. The valve type should also be indicated by circling the appropriate type. The order of power transfer of the assemblies in the structure should be numbered; for example, in Fig. 8 the order is 1) Hydraulic Cylinder, 2) Rocker Arm, and 3) Strut. The numbering for this example is shown below.

ASSEMBLY LIST AND ORDER OF POWER TRANSFER

	COMMON	LEFT	RIGHT
Exposed Gear			
Enclosed Gear			
Gear Rack			
Strut Arm	3		
Rocker Arm	2		
Cable			
Chain			
Hydraulic Cylinder	1		
Coupling			

The appropriate inspection pages for the selected assemblies will then be completed and combined with the Page 1 and 2 for a complete set of inspection forms. If the valve shown in Fig. 8 was inspected, one hydraulic cylinder Parts 1 and 2, one rocker arm page, and one strut arm page must be added to the Page 1 and Page 2 for a complete set.

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Page 2 comments: Historical or General Data.

Completed prior to the site inspection and verified or changed during the site inspection.

Operating equipment components are sometimes replaced or removed during rehabilitation. It is important for later reference to record the history of the in-place structure.

Enter major MAINTENANCE, REPAIRS, OR OTHER MODIFICATIONS performed on the operating equipment within the past 10 years.

Enter PREVIOUS INSPECTION information for reference purposes.

43
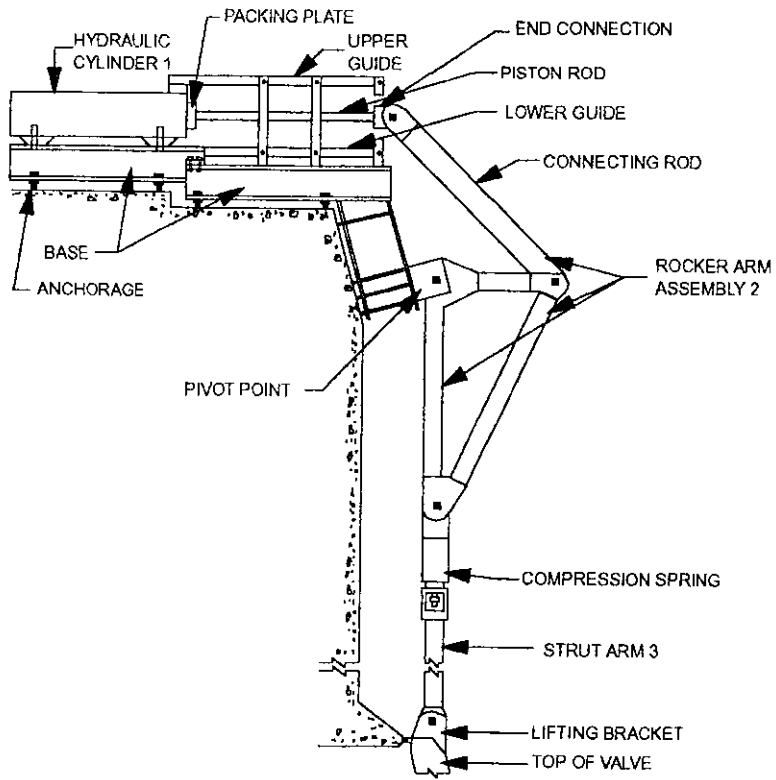
Figure 8. Side View of Tainter Valve Operating Equipment

Page 1. Comments: Recordkeeping Data

Completed before the site inspection and verified or changed during the site inspection.

Enter the NAME of the Corps of Engineer Project Title.

Indicate the BODY OF WATER and NEAREST TOWN.

Indicate type of gate for the GATE IDENTIFICATION.

Select ASSEMBLIES that exist in the operating equipment and number them in order of POWER TRANSFER from source of power to the structure. If the equipment splits into a LEFT and RIGHT set of equipment, place the power transfer number in the columns labeled left and right, respectively. Place an L behind the number if it is on the left side and an R behind the number if it is on the right side. If the assembly is common to (shared by) both sides or if there is no power split, place the numbers in the COMMON column. Left and right are determined when facing downstream.

Example: One Page 1 can be used for any combination of assemblies used to operate a dam gate. The gate type should be indicated by circling the appropriate type. The order of power transfer of the assemblies in the structure should be numbered; for example, in Fig. 10 the order is 1) Coupling, 2) Enclosed Gears, 3) Coupling, 4) Enclosed Gears, 5) Coupling, 6L) Exposed Gears, 6R) Coupling, 7L) Cable, 7R) Coupling, 8R) Exposed Gears, and 9R) Cable. The numbering for this example is shown below.

ASSEMBLY LIST AND ORDER OF POWER TRANSFER

	COMMON	LEFT	RIGHT
Exposed Gear		6L	8R
Enclosed Gear	2, 4		
Gear Rack			
Strut Arm			
Rocker Arm			
Cable		7L	9R
Chain			
Hydraulic Cylinder			
Coupling	1, 3, 5		6R, 7R

The appropriate inspection Parts 1 and 2 for the selected assemblies will then be completed and combined with the Page 1 and 2 for a complete set of inspection forms. If the dam gate operating equipment shown in Fig. 10 was inspected, five coupling pages, two enclosed gear Parts 1 and 2, two exposed gear Parts 1 and 2, and two cable Parts 1 and 2 must be added to the Page 1 and Page 2 for a complete set.

Page 2 comments: Historical or General Data.

Completed prior to the site inspection and verified or changed during the site inspection.

Operating equipment components are sometimes replaced or removed during rehabilitation. It is important for later reference to record the history of the in-place structure.

Enter major MAINTENANCE, REPAIRS, OR OTHER MODIFICATIONS performed on the operating equipment within the past 10 years.

Enter PREVIOUS INSPECTION information for reference purposes.
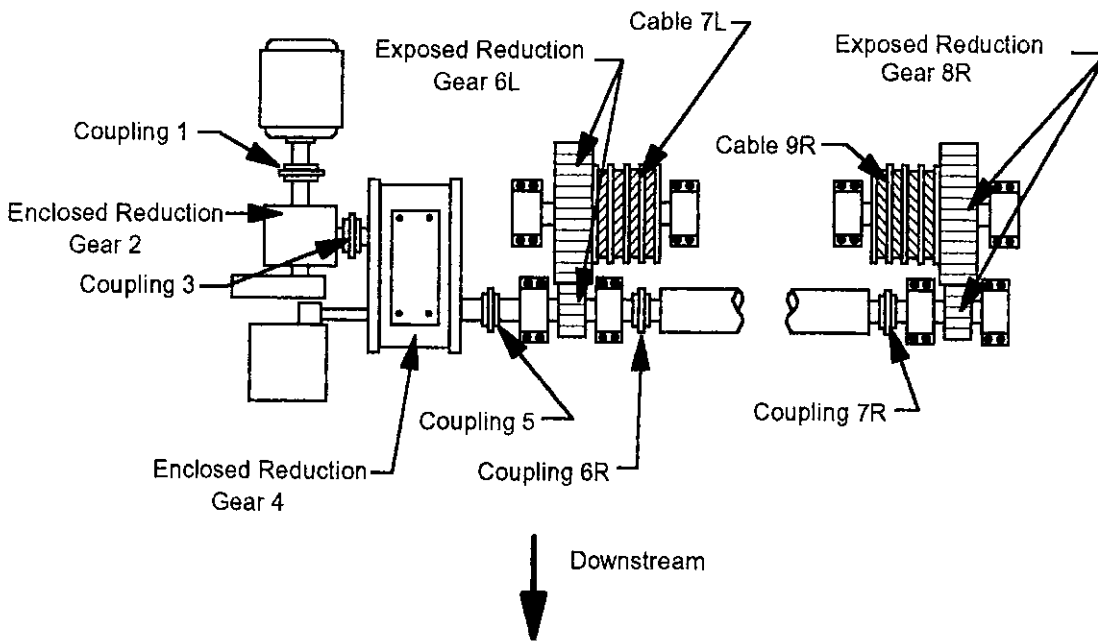
Figure 10. Plan View of Dam Gate Operating Equipment

CHAPTER 4. EXPOSED GEAR ASSEMBLY

Component Identification

Definitions and sketches for components of the exposed gear assembly are presented in the following paragraphs. Sector gears and bull gears, which are used with the rack assembly on lock and dam gates, are included in this assembly. The inspection form and rules for racks are presented in Chapter 6.

Sector Gear

A sector gear is a large gear in the shape of a partial circle. A sector gear transfers force from the roller rack to a linkage arm through rotation (Fig. 6). The linkage arm is secured to and rotates with the sector gear. Sector gears rotate on either a bushing or bearing system. Sector gears often have counter weights or are supported by a roller system to account for eccentric loads on the bushings or bearings.

Bull Gear

The bull gear consists of teeth arranged in a circular fashion and transfers force from the reduction gear set to the rack on a sector gate (Fig. 11). The gear rotates on either a bushing or a bearing system.

Reduction Gears

Reduction gears are a series of gears used to lessen the torque required to open and close or raise and lower gate or valve structures, respectively. As a result, the structure moves at a slower rate of speed then the motor rotates (Figs. 10,11,12).

ROLLER RACK

ELECTRIC MOTOR
WORM

WORM
GEAR

REDUCTION GEARS

SECTOR GATE

LOCK WALL

LOCK CHAMBER
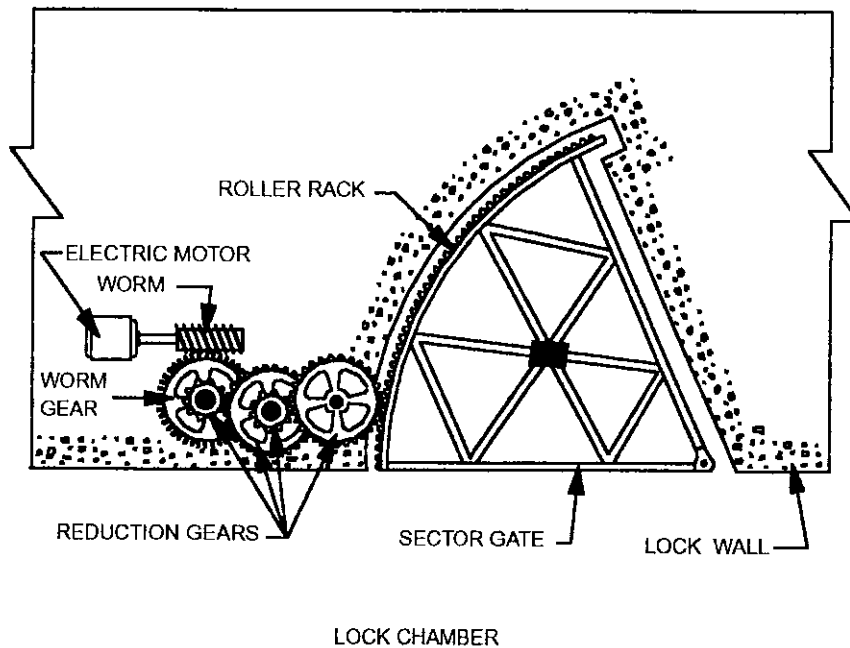
Figure 11. Plan View of Sector Lock Gate Operating Equipment (Gear and Rack)

Gear and Pinion

The gear and pinion are a set of reduction gears, one (pinion) substantially smaller than the other (gear), which act as reduction gears.

Roller Support

Large horizontal gears are often supported with roller systems.

Inspection Form With Comments

The following pages (Fig. 13) present Parts 1 and 2 of the field inspection forms for an exposed gear assembly. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).
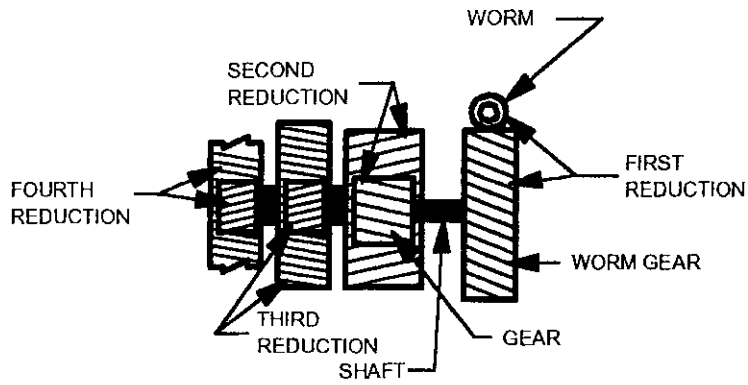
SECTION VIEW
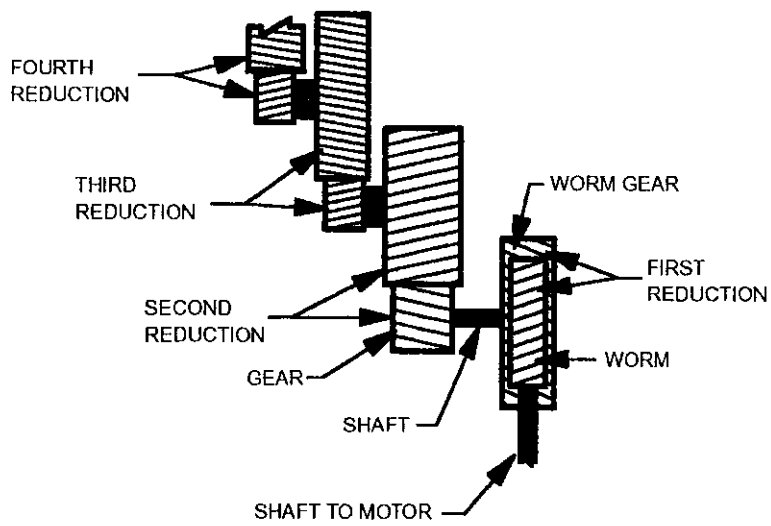
PLAN VIEW

Figure 12. Reduction Gear Schematic

PART 1 Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which gate leaf or valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the exposed gear during gate movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, and/or vibration is NORMAL.

Record the evidence of MOVEMENT of the gear ANCHORAGE system base as the gate is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement (Fig. 14). A dial gage change greater than 0.002 in. is considered movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment (Fig. 14). Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE NUTS at the gear anchorage if the BOLTS are EXPOSED (Fig. 14).

The presence of BEARING/BUSHING WEAR for the gear is determined by observing whether there is WOBBLE or TIPPING of the gear. Record whether there is wobbling or tipping of the gear. To check for wobble, watch the gear as it is operated. If the gear is not too large, bearing/bushing wear can also be checked by prying the gear while it is not being operated. Tipping of large horizontal gears can be observed by measuring the vertical distance from a gear tooth to a reference point on the concrete floor, rotating the gear to a closed position if it was open (or to an open position if it was closed) and measuring from the reference point on the concrete floor to the corresponding tooth directly above the reference point. For vertical gears, a horizontal reference point should be established to determine if wobbling occurs. When using this method to determine whether tipping occurs, the maximum lateral displacement in a bushing type gear is 1/16 in. per foot of radius and 1/16 in. per 3 feet of radius in a bearing type system. If the measured vertical displacement is greater than these maximums, record a yes (Y) for bearing/bushing wear. If the gear rotates on a BUSHING TYPE system and tipping is evident, record the MEASURED LATERAL DISPLACEMENT found by JACKING the gear. A detailed procedure for jacking the gear can be found in Appendix A. Also record the GEAR RADIUS in feet.

PART 2 Comments: Field data

Record a yes (Y) if the gear is ROLLER SUPPORTED. If the gear is roller supported, record if the ROLLERS TURN FREELY.   If the rollers do not turn freely, record if the GEAR OPERATION IS LIMITED.

The presence of CRACKS on the gear is usually not tolerated. Record the NUMBER OF CRACKS found on the gear by visual observation. Many times a crack will show up as corrosion underneath the painted surface. Also record the location of the cracks in the COMMENT section.

Record the average percentage of TOOTH CONTACT in the 5 teeth with the least contact area. The contact area is usually associated with an area where the grease film is noticeably thinner. Wear patterns may also help to identify the contact area. Once the contact area has been identified, the % CONTACT is recorded as the percentage of the total tooth area which is contacted area. Also, record where the CONTACT area LOCATION is, relative to the total tooth area. In the RADIAL DIRECTION, the location is recorded as occurring primarily at the tip (T), middle (M), root (R), or any combination of the three (Fig. 15). In the AXIAL DIRECTION, the location is recorded as occurring primarily on the top(P), center (C), bottom(B) or any combination of the three (Fig. 15). To determine the top side of the gear observe the gear from both sides as the gate or valve is being closed. The side from which the gear is turning counter-clockwise is the top side of the gear.

Pick the TOOTH with the worst WEAR and look at the wear at the pitch line. Record if there is TOOTH WEAR. If the pitch line is not scribed on the teeth, a good estimate of the pitch line location is slightly towards the tip from the mid-depth of the tooth. If tooth wear is visible, estimate the PERCENTAGE of TOOTH THICKNESS REDUCTION. The percentage of thickness reduction can be estimated a number of ways. One technique is to measure both a worn tooth and a tooth which has infrequent contact with a ruler or tape measure and compare the tooth thicknesses. A second technique to estimate the thickness reduction of tooth thickness on meshing gears with different widths is to check for a worn ledge on the wider tooth, with the depth of the ledge being the estimate of reduction in thickness. A third technique is to observe the curvature of a worn tooth and a tooth which has infrequent contact. As the tooth wears, the tooth edge may become flat. If the estimated percentage is greater than 10%, record the MEASURED percentage using wear measurement techniques in Appendix B.

Pick the worst DAMAGED TOOTH for each type of damage on each gear and record the percentage of SURFACE AREA which is missing due to CHIPPING, DEFORMATION, PITTING, CORROSION, or GOUGING. If damage has occurred indicate the TYPE of DAMAGE. Chipping of the tooth is the breaking off of steel pieces, which usually results in jagged edges and high stress concentrations in the tooth. Deformation of the tooth is the changing of the shape of the tooth, usually the result of excessive forces or something

PART 2 Comments: Field data (continued)

becoming lodged in between teeth during operation. Pitting of the tooth is the severe localized corrosion of the tooth which results in small cavities in the tooth surface. Corrosion is the loss of steel in the tooth due to interaction with the environment. Gouging of the tooth is the occurrence of smooth grooves or holes in the tooth surface. Record the LOCATION of the damaged teeth. The location of the tooth is described by a number. On a sector gear, the first tooth on the side where the sector arm is connected is tooth number one and will be numbered from there. For bull gears which engage the sector gate rack, the gear tooth which is fully in contact with the rack when the gate is in the open position is numbered one and the remaining teeth will be numbered in counter-clockwise direction from tooth one. For exposed reduction gears, the meshing teeth between the gears which are fully in contact when the gate or valve is in the open position is numbered one. The remaining teeth are numbered in order starting at tooth one and going in the direction the gear turns as the gate or valve is being closed.

Figure 13. (continued)
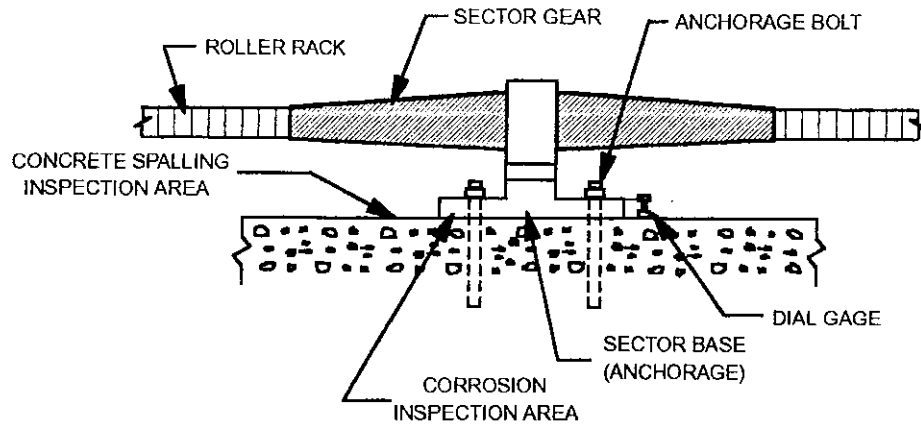
Figure 14. Gear Anchorage Movement/Deterioration Measurement
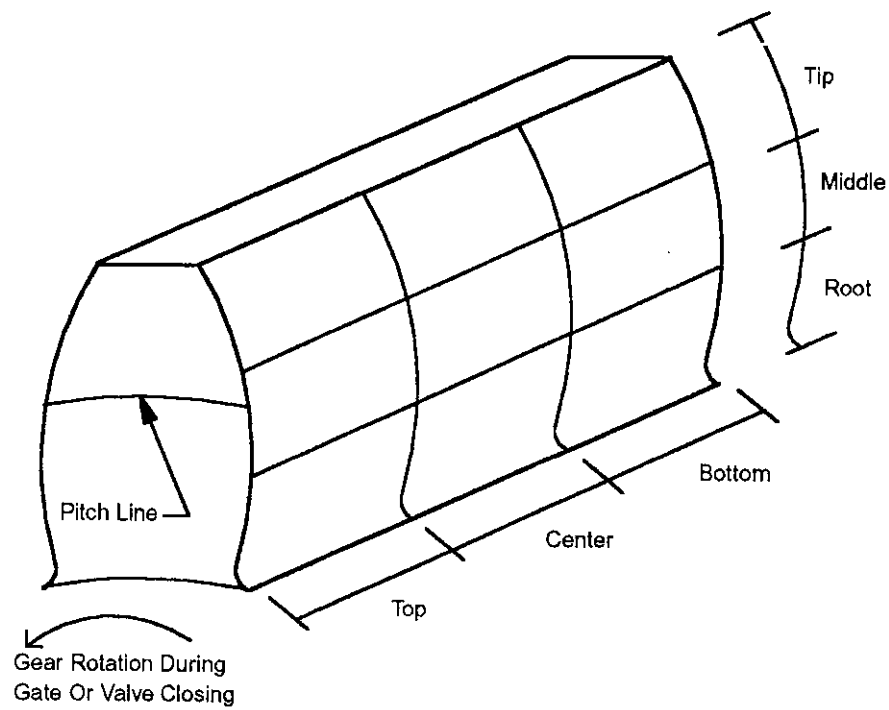
Figure 15. Tooth Contact Location

Condition Index Rules

The following section contains the rules for calculating the individual CI₁s and the

assembly CIs for the exposed gear assembly. Distress descriptions and example illustrations

are also provided.

Noise, Jumping, and Vibration

Definition and Causes: This distress represents abnormal sounds and motions of the

exposed gear assembly during operation. Although a noise is often difficult to isolate and

diagnose, abnormal noises should not be ignored because they commonly indicate a problem.

Abnormal noises, jumping, and vibrations are caused by several factors including improper

lubrication, wear, misalignment [23], tooth contact loss [24], and tooth errors such as spacing

problems [25]. It is important to monitor vibrations as they will often remain the same for

years, but will begin to change as components wear [26]. Obviously, this distress is more

subjective and less quantifiable than many distresses; however, its importance should not be

minimized. Jumping, for example, can indicate the presence of an assembly problem.

Abnormal noises almost always indicate behavior which should be investigated.

Measurement and Limits: The noise, jumping, and vibration distress is recorded

when it occurs at any point in the operation sequence. The CI for the possible combinations is

shown below:

Noise, Jumping, or Vibration	CI
None	100
Yes for anyone of the three	70
Yes for any two	40
Yes for all three	30

Example: During the operation of an exposed gear assembly, a grinding sound could be heard. The CI is

$$CI = 70$$

because the grinding sound is abnormal for an exposed gear assembly. Table 2 shows this CI as being good.

Anchorage Movement/Deterioration

Definition and Causes: Anchorage movement and deterioration represents the displacement of the embedded anchorage system and the current condition of the assembly components, especially the gear casting and anchorage bolts. Movement can occur during opening and closing of the gate or valve structure. The anchorage system is the only mechanism that connects the gear to the concrete. Hence, the presence of anchorage movement may indicate a significant structural problem, or it could eventually introduce structural problems into other parts of the operating equipment power transfer setup. In addition, corroded, loose, or missing casting and anchorage bolts can cause irregular movement of the equipment introducing functional and structural problems into various components.

Measurement and Limits: If anchorage movement is detected visually or if a movement of 0.002" or greater is registered on the dial gage, the movement is considered significant. Any movement reduces the CI to 40. Any structural cracking or spalling of the concrete in this area will reduce the condition index by a factor of 0.85 (Fig. 14). This is also the case for a corroded embeddment at this location, i.e., an additional 0.85 reduction. In addition, if any of the exposed bolts or nuts are significantly corroded, the CI decreases by a

factor of 0.70. If any of the anchor or casting nuts are loose, the CI is reduced by a factor of 0.55. If any bolts or nuts are broken or missing, the CI is decreased by a factor of 0.40. If there are multiple gear sets in an assembly, the anchorage movement/deterioration CI for the assembly is the minimum of the anchorage movement/deterioration CIs of the gear sets making up that assembly.

Example: The anchorage for an exposed gear assembly was found to have cracked concrete around the anchorage base. In addition, some of the exposed bolts were significantly corroded. There was no detectable movement, therefore, the CI is

$$CI = [100][0.85][0.70] = 60$$

Table 2 shows that this CI is fair.

Bearing/Bushing Wear

Definition and Causes: A bearing or bushing separate the axle and the gear. The axle casting is rigidly attached to the anchorage system, while the bearing or bushing is free to rotate. Bearing/bushing wear refers to the total relative movement of the gear with respect to the axle. This wear can be caused by normal use, excessive forces, misaligned gears, or inadequate lubrication.

Measurement and Limits: Wear in the bearing or bushing is determined by observing the wobbling or tipping in the gear. If significant wobbling or tipping in a gear is recorded (1/16 in. per foot of gear radius in a bushing system and 1/16 in. per 3 feet in a bearing system), the CI can be no higher than 70. If a yes is recorded for wobbling or tipping and the gear rotates on a bushing type system, a vertical displacement, X, is recorded by a jacking procedure. The limiting value for this vertical displacement is

$$X_{MAX} = \text{5/32 in. per foot of radius} \tag{4.1}$$

If there are multiple gears in an assembly, the bearing/bushing wear CI for the assembly is the minimum of the CIs for bearing/bushing wear of the gears making up that assembly.

Example: Tipping of a bushing type gear was detected. A vertical displacement of

$$X = \text{5/16 in.}$$

was measured. The gear has a radius of 3 feet. The limiting value of the vertical displacement for this gear is

$$X_{MAX} = \text{15/32 in.}$$

The CI for bushing wear is

$$CI = 100(0.4)^{(5/16)/(15/32)} = 54$$

The CI is marginal.

Roller Support Wear/Damage

Definition and Causes: The roller support distress refers to the wear or corrosion of the bearing or bushing system for the gear roller supports, if they exist. Wear or corrosion of the roller bearing or bushing can cause the roller to freeze and become incapable of rolling. This distress can be caused by normal use, improper alignment, or interaction with the environment.

Measurement and Limits: Wear or corrosion in the rollers is determined by observing whether the rollers turn freely during the operation of the equipment. If the rollers do not turn freely, the CI is 70. If the roller damage affects the operation of the gear, the CI is 40. If the exposed gear is not roller supported, no CI will be calculated and the CI for the exposed gear assembly will not be affected by the roller support distress. If there are multiple

gears in an assembly, the roller support wear/damage CI for the assembly is the minimum of the roller support wear/damage CIs of the gears making up that assembly.

Example: During the operation of a roller supported exposed gear, the rollers did not turn freely. The CI for the roller support distress is

$$CI = 70$$

The CI is rated marginal.

Cracks

Definition and Causes: Cracks usually represent a narrow opening, break, or discontinuity in the steel members. Cracks are caused by fatigue, brittle fracture, or over-stressed steel components. Obviously, cracks have significant structural implications because they can continue to grow if the cause of the over-stress still exists or if the remaining steel cross section cannot carry the normal loads.

Measurement and Limits: The number of cracks on the teeth and frame of the gear are recorded on the inspection form. The limiting value for a exposed gear is one crack,

$$X_{MAX} = 1 \tag{4.2}$$

which is considered critical [24]. A crack on the gear reduces the CI to 40. If there are multiple gears in an assembly, the cracks CI for the assembly is the minimum of the cracks CIs of the gears making up that assembly.

Example: One crack was found on an exposed gear during an inspection. The CI for this distress is

$$CI = 100(0.4)^{1/1} = 40$$

The CI is rated marginal.

Reduced Tooth Contact

Definitions and Causes: The tooth contact distress is the reduction in contact area or engagement surface between meshing teeth. This distress can be caused by normal wear, uneven wear, or misalignment of gears.

Measurements and Limits: The percent of contact, X_1, is found by observing the grease on the face of the gear teeth. The percent of tooth not in contact is

$$X = 100\% - X_1 \qquad\qquad (4.3)$$

The limiting value for the percentage of non-contact on gear teeth is

$$X_{MAX} = 75\% \qquad\qquad (4.4)$$

If there are multiple gears in an assembly, the reduced tooth contact CI for the assembly is the minimum of the reduced tooth contact CIs of the gears making up that assembly.

Example: The percentage of contact on a gear tooth was

$$X_1 = 40\%$$

The percentage of the tooth not in contact was

$$X = 100\% - 40\% = 60\%$$

The CI for tooth contact is

$$CI = [100(0.4)^{(60/75)}] = 48$$

The CI is rated fair.

Tooth Wear

Definition and Causes: Tooth wear is the deterioration of gear teeth as corresponding teeth engage. The causes of this distress can be attributed to normal wear, inadequate lubrication, excessive loads, and improper gear alignment.

Measurement and Limits: Gear tooth wear will be measured by recording the estimated or measured percentage of tooth thickness loss at the pitch line, X. The limiting value is

$$X_{MAX} = 25 \% \tag{4.5}$$

If there are multiple gears in an assembly, the tooth wear CI for the assembly is the minimum of the tooth wear CIs of the gears making up that assembly.

Example: The percentage of lost thickness of a gear tooth at the pitch line was measured to be

$$X = 15\%$$

during an inspection. The CI from Equation 2.1 is

$$CI = [100(0.4^{15/25}] = 58$$

The CI is rated fair.

Damaged Teeth

Definitions and Causes: Stress in gear teeth increases as the surface area is decreased or stress concentrations are introduced. Damage to teeth may lead to failure due to the reduction in surface area and the introduction of stress concentrations. This distress could be caused by factors including inadequate lubrication, excessive force on teeth, or misalignment of teeth [24].

Measurements and Limits: The percentage of lost surface area on gear teeth, X, is recorded in the inspection process. The limiting value for damaged teeth is dependent on the type of damage. In cases where the tooth has been chipped or deformed, the limiting value is

$$X_{MAX} = 20\% \tag{4.6}$$

If the tooth is corroded, pitted, or gouged the stress concentrations will be lower and the limiting value is

$$X_{MAX} = 40\% \tag{4.7}$$

If there are multiple gears in an assembly, the damaged teeth CI for the assembly is the minimum of the damaged teeth CIs of the gears making up that assembly.

Example: The percent of contact area that was chipped on a gear tooth was

$$X = 15\%$$

The CI for damaged gear teeth is

$$CI = [100(0.4)^{15/20}] = 50$$

The CI is rated marginal.

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the exposed gear assembly is the cracks distress. The CI_is from the remaining seven distresses will be used to calculate the weighting factor assembly CI_w (Equation 2.5). The weighting factors for those seven distresses are in Table 13.

Field Test

Twenty exposed gear assemblies were observed during the field tests. The bar charts in Figures 16, 17 and 18 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective CI during the various field tests to the CI calculated from the exposed gear rules for three exposed gear distresses. Assemblies with no distresses are not plotted. Comparisons between the calculated and experts condition indexes are summarized below.
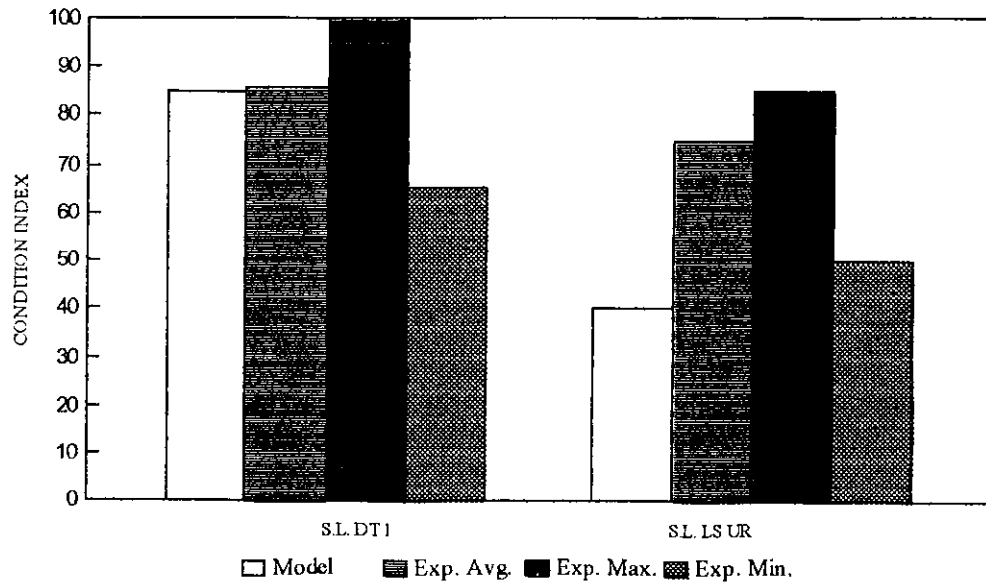
Figure 16. Anchorage Movement/Deterioration: Exposed Gear Assembly
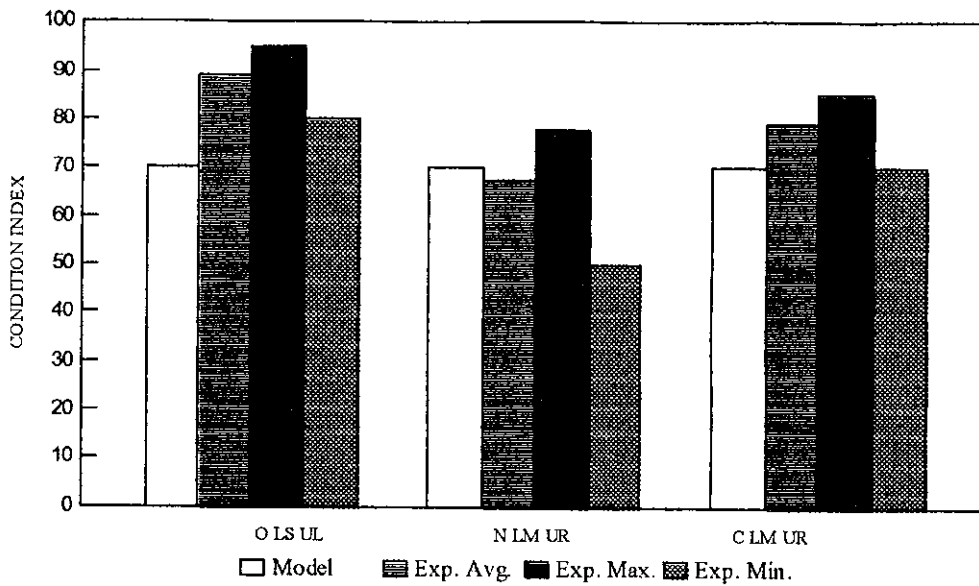
Figure 17. Bearing/Bushing Wear: Exposed Gear Assembly
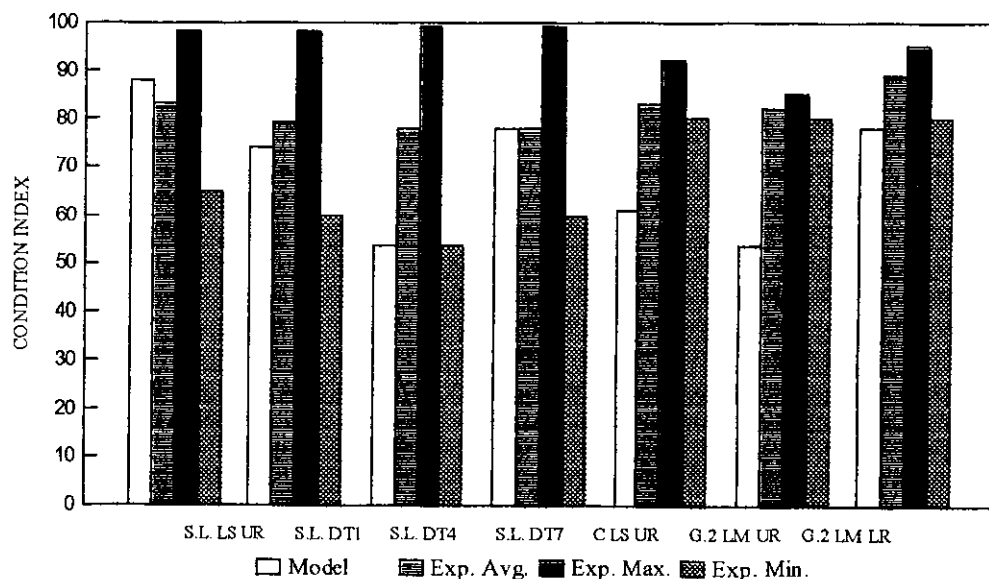
Figure 18. Reduced Tooth Contact: Exposed Gear Assembly

Noise, Jumping, and Vibration

Because no abnormal noise, jumping, or vibration was recorded, the calculated CI

values were 100. Although this distress was not recorded, the experts' average was below 90

on three of sixteen assemblies which were rated. However, in each of these three cases the

experts' average was 85 or greater. The noise, jumping, and vibration distress was calibrated

in the enclosed gear assembly.

Anchorage Movement/Deterioration (Fig. 16):

The anchorage movement/deterioration distress was observed only twice on the

operating equipment field tests in exposed gear assemblies. Corroded nuts were observed on

an exposed reduction gear set (Tainter Dam Gate St. Lucie #1) and anchorage movement was

observed on a bull gear (Upper Right Sector Lock Gate St. Lucie). The calculated CI for a

corroded nut (85) closely approximates the experts' averaged CI (86). The calculated CI for

anchorage movement (40) is 35 points lower than the experts' average (75) for the one case

which was observed. In later conversation with the experts, some said they had not rated the

distress lower because they felt it could be fixed by merely tightening the bolts. They did

agree, however, that the CI should have been lower than 75 if the problem was not fixed. For

the remainder of the exposed reduction gear assemblies which were observed the calculated

CIs were 100 and the experts' average CIs were above 90.

Bearing/Bushing Wear(Fig. 17):

The bearing/bushing distress was observed once (Ortona Upper Left Lock Gate)

during the field tests using the current rules. In this case the calculated CI is 70 and the

experts' average CI was 89. In two other cases bushing wear was observed using the jacking

technique described in Appendix A (Newburgh Upper Right Miter Lock Gate and Cannelton

Miter Lock Gate Main Chamber). For these cases, the calculated CIs (70 and 70),

respectively, and the experts' average CIs (68 and 80), respectively, are in better agreement.

Roller Support Wear/Damage

The roller support wear/damage distress was not calibrated because no damage to any

roller supports was observed in the exposed gears. Hence, the calculated CIs were all 100

and the experts' averaged CIs were 90 or above.

Cracks

The cracks distress was not calibrated because there were no cracks observed in the

exposed gears. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90

or above. Although this distress was not calibrated the experts feel that cracks in the gear are

critical and should be repaired, which corresponds well to the rules for exposed gears.

Reduced Tooth Contact (Fig. 18):

The reduced tooth contact distress and tooth wear distress were initially combined as one distress. Discussion with the experts near the end of the Louisville District field test resulted in separating the initial distress into two distinct distresses - tooth contact and tooth wear. Although no data was collected after the separation of the distresses, the data collected for the original combined distress was used to calibrate the tooth contact distress. The authors feel this is appropriate for two reasons: 1) the observed wear of the gear teeth was relatively low and 2) the weighting factor given by the experts for tooth contact was higher than the weighting factor for tooth wear (Table 13). In three cases (Tainter Dam Gate #4 St. Lucie, Miter Lock Gate Upper Right Cannelton, and Miter Gate Upper Right Green River #2) where the tooth contact distress was observed, the calculated CIs were between 22 to 30 points lower than the experts' average CIs. In all three of these cases the calculated CIs were in Zone 2. In the other four cases, the calculated CIs were all within 8 points of the expert average CIs.

Tooth Wear

Discussion with the experts near the end of the Louisville District field test resulted in a separation of the tooth wear and tooth contact distresses (see previous paragraph). Therefore, while the tooth wear distress was observed, calibration of the new rules is not possible with the current data. The new rules for tooth wear have, however, been constructed using the experts' judgement and advice.

Damaged Teeth

The inspection form questions and rules for the damaged teeth distress have changed

significantly since the first field test. The current questions and rules were formulated during

discussion with experts following the second field test. Therefore, while damaged teeth were

observed, calibration of the new rules is not possible with the current data. The new rules for

damaged teeth have, however, been constructed using the experts' judgement and advice.

Assembly CI (Fig. 19):

The assembly CI for exposed gear assembly was calibrated for three assemblies. In

each case the model CI was higher than the experts' average CI. Although the model CIs

were higher, the experts' average CIs and the model CIs were all in Zone 1.
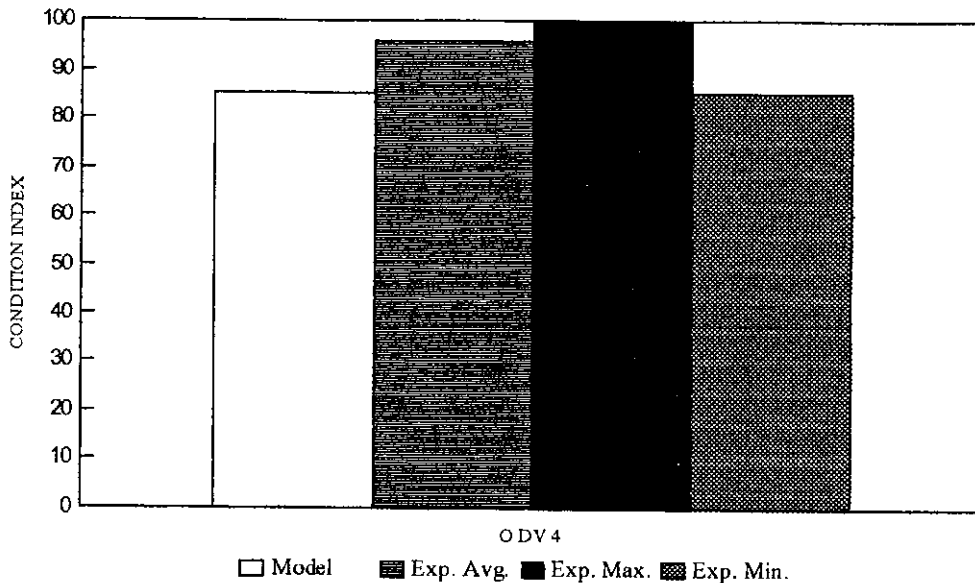
Figure 19. Exposed Gear Assembly CI

CHAPTER 5. ENCLOSED GEAR ASSEMBLY

Component Identification

Definitions and sketches for components of enclosed gear are presented in the following paragraphs.

Reduction Gears

Reduction gears are a series of gears used to lessen the torque required to open and close or raise and lower gate or valve structures, respectively. As a result, the structure moves at a slower rate of speed than the motor rotates (Fig. 10, 11). Enclosed reduction gears are located in a gear box and can sometimes be seen by removing the cover plate. The gears in the gear box are lubricated with an oil or grease bath.

Gear and Pinion

The gear and pinion are a set of reduction gears, one (pinion) substantially smaller than the other (gear), which act as reduction gears.

Transfer Box

The transfer box is a set of reduction gears which redirects the rotating shaft by ninety degrees (Fig. 10,12). This is accomplished with the use of a worm and a worm gear or with bevel gears.

Inspection Form With Comments

The following pages (Fig. 20) present Parts 1 and 2 of the field inspection forms for an enclosed gear assembly. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

PART 1 Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which gate leaf or valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the enclosed gear during gate or valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, and/or vibration is NORMAL.

Record the evidence of MOVEMENT of the gear ANCHORAGE system base of the gear as the gate is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement (Fig. 14). A dial gage change greater than 0.002 in. is considered movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment (Fig. 14). Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE NUTS at the gear anchorage if the BOLTS are EXPOSED (Fig. 14).

The presence of CRACKS on the gear is usually not tolerated. Sometimes a cover plate can be removed and the gears can be observed. If the GEARS CAN BE OBSERVED record the NUMBER OF CRACKS found on the gear by visual observation. Many times a crack will show up as corrosion underneath the painted surface. Also record the location of the cracks in the COMMENT section.

Sometimes a cover plate on the gear box can be removed and the gear teeth can be observed. If the GEAR TEETH CAN BE OBSERVED, pick the worst DAMAGED TOOTH for each type of damage on each gear and record the percentage of SURFACE AREA which is missing due to CHIPPING, DEFORMATION, PITTING, CORROSION, or GOUGING. If damage has occurred indicate the TYPE of DAMAGE. Chipping of the tooth is the breaking off of steel pieces, which usually results in jagged edges and high stress concentrations in the tooth. Deformation of the tooth is the changing of the shape of the tooth, usually the result of excessive forces or something becoming lodged in between teeth during operation. Pitting of the tooth is the severe localized corrosion of the tooth which results in small cavities in the tooth surface. Corrosion is the loss of steel in the tooth due to interaction with the environment. Gouging of the tooth is the making of smooth grooves or holes in the tooth surface. Record the LOCATION of the damaged teeth, described by a number. The meshing teeth between the gears which are fully in contact when the gate or valve is in the open position is numbered one. The remaining teeth are numbered in order going in the counter-clockwise direction, which is determined as the gate or valve is being closed.

PART 2 Comments: Field data

Excessive TEMPERATURE RISE of THE GEAR BOX is often an indication that something
is not operating properly. A temperature rise can be observed by placing a hand on the gear
box during operation. Record if there is a SLIGHT or SIGNIFICANT TEMPERATURE
RISE of THE GEAR BOX. Record if there is EVIDENCE OF RECENT LEAKAGE.
Record the NUMBER of OIL DROPS that leak from the gear box during one operating
CYCLE. One cycle for a lock gate or valve is to open and then close the structure or vice-
versa. For a dam gate, one cycle is completed by opening the gate 2 feet and then closing it.
Record if any WATER is PRESENT in the OIL. Many times water which is present will
appear as a milky ribbon throughout the oil. Record if any DIRT or RUST is PRESENT in
the OIL. Also record if there is any METAL PRESENT IN the OIL. This can be
accomplished by taking a small sample of oil and subjectively observing the quality of the oil.
Record if an OIL SAMPLE HAS been TAKEN. If YES, record the DATE WHEN it was last
tested and if the OIL MEETS manufacturer SPECIFICATIONS.

Condition Index Rules

The following section contains the rules for calculating the individual CIs for the enclosed gear assembly distresses and the assembly CI. Distress descriptions and example illustrations are also provided.

Noise, Jumping, and Vibration

See noise, jumping, and vibration for the exposed gear assembly (Chapter 4)

Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Damaged Teeth

See damaged teeth for the exposed gear assembly (Chapter 4)

Temperature Rise of Gear Box

Definition and Causes: Excessive temperature change is often an indication that the enclosed gears are not operating properly. While high temperatures are not harmful to the gear itself, they may be detrimental to seals and to the oil itself [26]. Excessive temperature change can be caused by inadequate lubrication, misaligned gear teeth, or excessive loads on the enclosed gear assembly.

Measurement and Limits: The temperature change of the oil in the gear box which can be felt by the hand is recorded. If a slight temperature rise is observed, the CI is 70. If a significant temperature rise is observed, the CI is 40.

Example: During the operation of an enclosed gear, a slight temperature rise was observed.

The CI for the temperature rise of the gear box distress is

$$CI = 70$$

The CI is rated good.

Oil Leakage

Definition and Causes: Fresh oil stains, dripping oil, or standing oil are signs of oil leakage. Oil leakage can be an indication of other problems in the operating equipment or caused by worn seals or gaskets on the gear box.

Measurement and Limits: The number of oil drips per operation cycle are recorded in the inspection form. One cycle of a lock gate or valve is completed by opening and then closing the structure or vice-versa. For a dam gate a cycle is completed by opening the gate 2 feet and then closing it. If drops of oil are observed leaking during the operation of the enclosed gear, the limiting value of oil leakage per cycle is

$$X_{MAX} = 3 \text{ drops} \tag{5.1}$$

The presence of any puddled oil or oil stains is also recorded. If there is evidence of recent oil leakage the CI can be no higher than 85.

Example: A sheet of paper was placed below an enclosed gear box during its operation. During one cycle, 3 drips of oil dropped to the paper. The CI for the oil leakage distress is

$$CI = 100(0.4)^{(3/3)} = 40$$

The CI is rated marginal.

Oil Contamination

Definition and Causes: All rotating equipment parts and machinery require lubrication to function properly. Over time the oil becomes contaminated and breaks down. The oil contamination distress is the reduction of the useful life of the lubrication oil. The contamination of the oil is caused by the collection of dirt, rust, water, and metal particles in the oil.

Measurement and Limits: Oil distress is measured at two different levels. The first level involves visually checking the oil consistency for: (1) water, (2) dirt or rust, and (3) metal. If water is present the CI is reduced by a factor of 0.85. Likewise, if dirt or rust are present a reduction factor of 0.85 is applied to the CI. If there is metal in the oil, the CI is 40. In the second level of inspection, a representative sample is examined in the laboratory for extended chemical analysis to check for particulate such as dirt, water, and rust on a more precise scale. The results of this test should be included in any inspection report that is generated. If the oil does not meet the specifications set by the manufacturer or laboratory, the CI is 40 [27].

Example: Upon inspection of a gear box, rust and water were found to be present in the oil. The CI for oil contamination is

$$CI = [100(.85)(.85)] = 72$$

From Table 1, the CI is rated good.

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the enclosed gear assembly is the cracks

distress. The CIs from the remaining six distresses will be used to calculate the weighted CI_w

(Equation 2.5). The weighting factors for those six distresses can be found in Table 14.

Field Test

Fifteen enclosed gear assemblies were observed during the field tests. The bar charts

in Figures 21 through 26 (see Tables 23 through 25 for the abbreviation definitions) compare

the experts' subjective condition index to the condition index calculated from the rules for the

six enclosded gear distresses which were observed during field tests. Comparisons between

the calculated and experts condition indexes are summarized below.
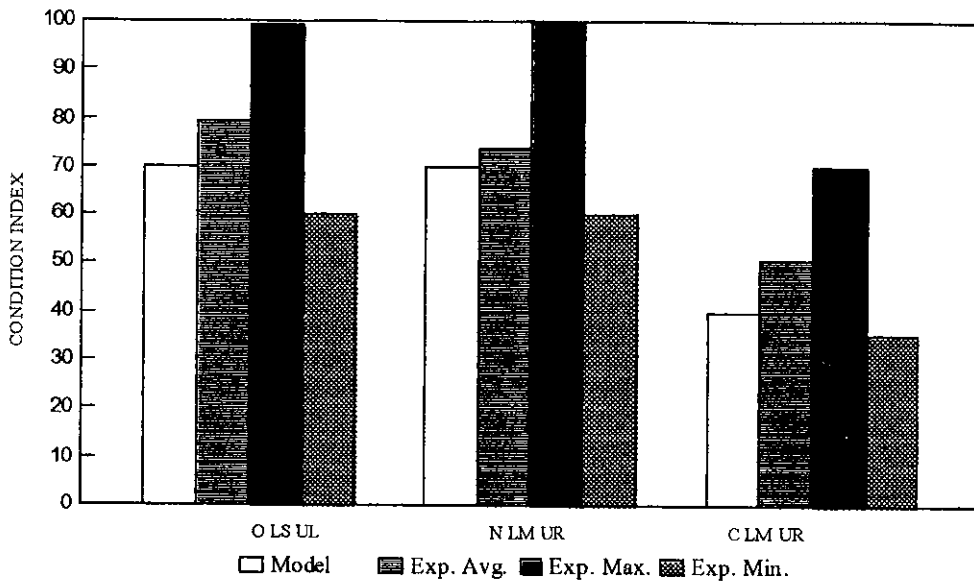
Figure 21. Noise, Jumping, and Vibration: Enclosed Gear Assembly
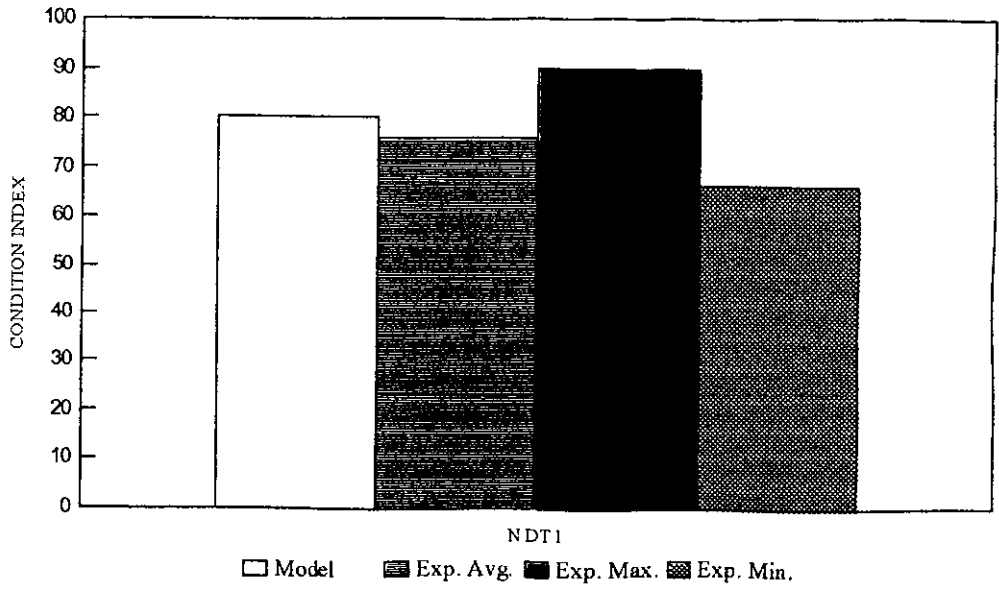
Figure 22. Anchorage Movement/Deterioration: Enclosed Gear Assembly
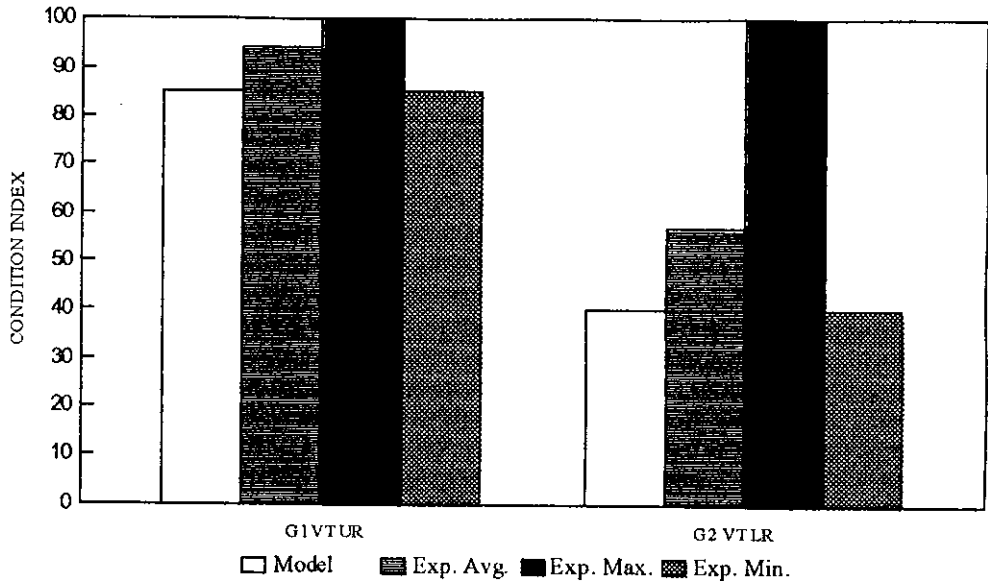
Figure 23. Damaged Teeth: Enclosed Gear Assembly

Figure 24. Temperature Rise of Oil: Enclosed Gear Assembly
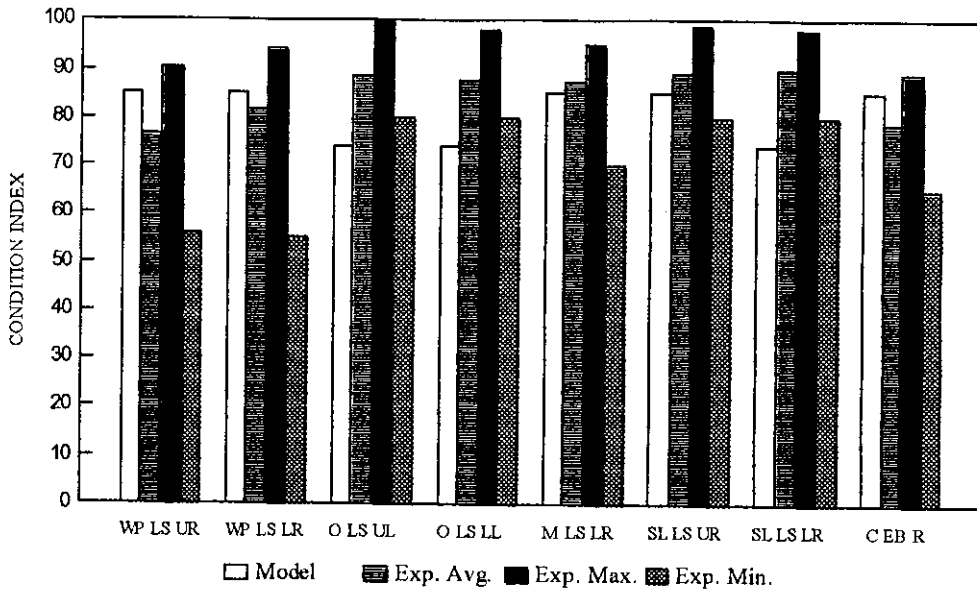
Figure 25. Oil Leakage: Enclosed Gear Assembly

CONDITION INDEX

100
90
80
70
60
50
40
30
20
10
0

WP LS UR   WP LS LR   M LS UR   M LS LR   SL LS LR   SL DT1   SL DT 7   N DT 1

☐ Model   ▨ Exp. Avg.   ■ Exp. Max.   ▨ Exp. Min.
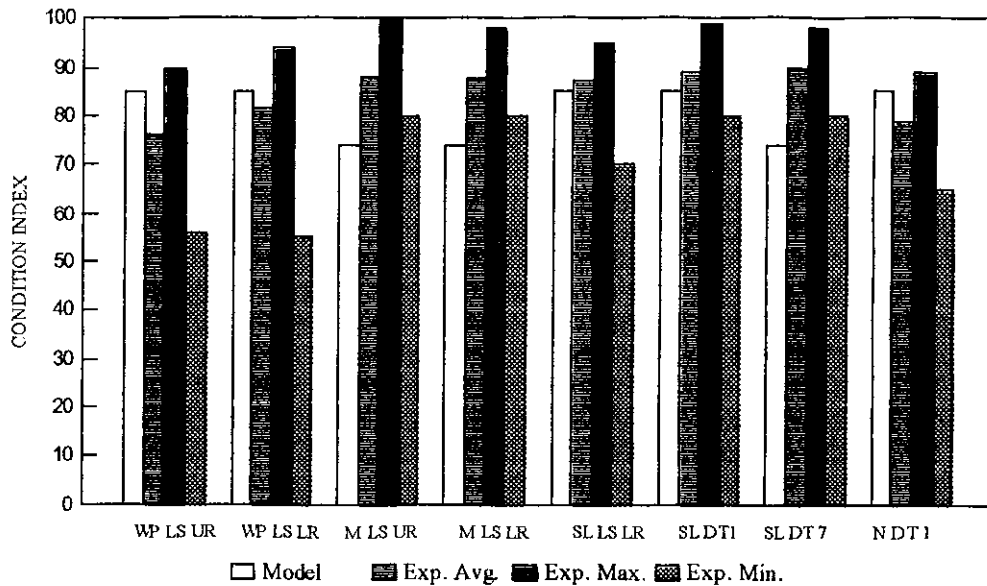
Figure 26. Oil Contamination: Enclosed Gear Assembly

Noise, Jumping, and Vibration (Fig. 21):

In twelve of the fifteen observed exposed gear assemblies, the noise, jumping, and vibration distress was not observed; therefore, the calculated CIs were 100 and the experts averaged CIs were above 90. In one case (Upper Right Lock Gate Moore Haven) a thumping noise was heard in the gear box. The calculated CI is 70, while the experts' average CI was 80. In another case, jumping was observed(Upper Right Lock Gate St. Lucie); therefore, the calculated CI was 70. The experts' average CI was 74. The enclosed gear used to operate Dam Gate #1 on the St. Lucie Dam was observed as making a noise and vibrating. The calculated CI for noise and vibration is 40. The experts average CI dropped to 51.

Anchorage Movement/Deterioration (Fig. 22):

The anchorage movement/deterioration distress could be calibrated for only two enclosed gear assemblies during the field tests as the distress was not observed in the other

assemblies during the field tests. Corroded anchorage nuts were observed at one location (Upper Right Lock Gate Moore Haven) in which case a CI of 85 was calculated. The experts did not seem to consider the corrosion significant, as their average CI was 94. Anchorage movement of a different anchorage system (Lower Right Lock Gate St. Lucie) was detected and a CI of 40 was calculated. The experts average CI of 57 was considerably lower than 100; however, it was still 17 points higher than the calculated CI.

Cracks

The cracks distress was not calibrated because there were no cracks observed in the enclosed gears. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above. Although this distress was not calibrated the experts feel that cracks in an enclosed gear are critical and should be repaired, which corresponds well to the rules for enclosed gears.

Damaged Teeth (Fig. 23):

Only one case of damaged teeth in enclosed gears was observed (Dam Gate #1 Newburgh). In this case the calculated CI was 80 and the experts' average CI was 76.

Temperature Rise Of Oil (Fig. 24):

The temperature rise of oil was observed twice in the field testing of enclosed gear assemblies (Lower Right Lock Gate St. Lucie and Tainter Dam Gate #1 St. Lucie). In both cases the calculated CI is 70. The experts' averaged CI varied greatly in the two cases. With a slight temperature rise of the reduction gear box on the Lower Right Lock Gate, the experts' average was 85, while the experts' average was 58 when a temperature rise occurred in the gear box on the Tainter Dam Gate #1. The difference in the experts' CIs could be based on

the difference in temperature change in the two cases; that is, the temperature change in the second case was greater.

Oil Leakage (Fig. 25):

The oil leakage distress was observed in eight of the fifteen enclosed gear assemblies. The experts' average CIs varied from 9 points below to 15 points above the calculated CIs.

Oil Contamination (Fig. 26):

Dirt or water was observed in eight of the fifteen enclosed gear assemblies. The experts' average CIs varied from 10 points below to 6 points above the calculated CIs of 85. Metal filings were observed in one of the gear boxes (Tainter Dam Gate #1 St. Lucie). In this case the calculated CI was 40 and the experts' average CI was 53. In the remaining seven cases the distress was not observed and the experts' average CIs were all 90 or higher.

Assembly CI (Fig. 27):

The assembly CI for the enclosed gear assembly was calibrated for six assemblies. For four of the assemblies the model CIs were above the experts' average CIs and for the remaining two assemblies the model CIs were slightly lower. The corresponding model CIs and experts' average CIs were in the same zone for each of the six calibrated assemblies.
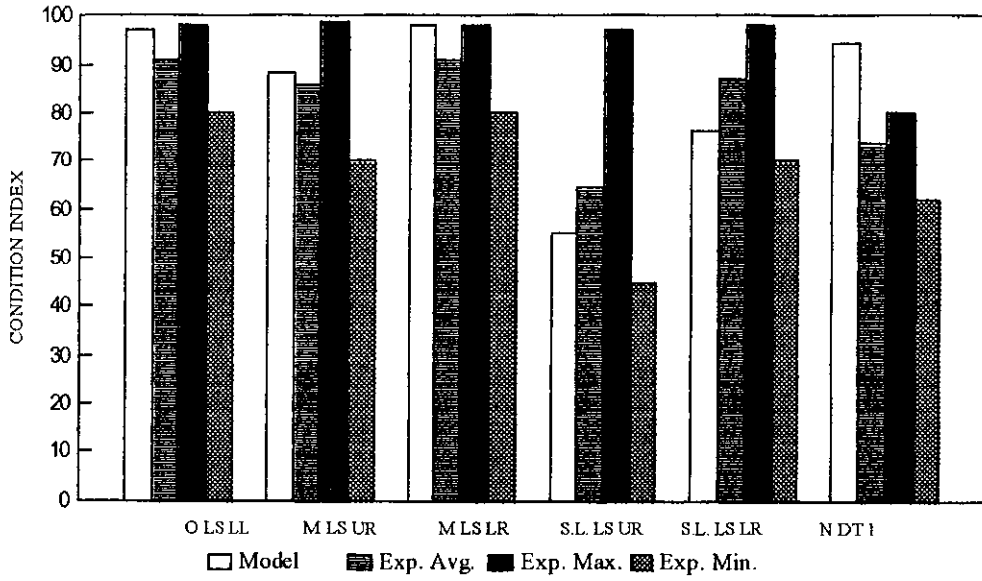
Figure 27. Enclosed Gear Assembly CI

CHAPTER 6. GEAR RACK ASSEMBLY

Component Identification

Definitions and sketches for components of the gear rack assembly are presented in the following paragraphs.

Rack

The rack consists of a set of teeth arranged in a linear or slightly curved fashion. Teeth on the rack mesh with matching teeth on the corresponding gear. The rack transfers force from the hydraulic cylinder to the sector gear when used to operate a miter gate (Fig. 6). When used to operate a sector gate, the rack is attached rigidly to the top of the gate and transfers force from a gear to the gate (Fig. 11). Racks are sometimes designed to perform as strut and rack assemblies simultaneously. These rack/strut members are used to operate sector lock gates and tainter dam gates.

Reaction rollers

Reaction rollers resist the lateral load on the rack by the gear as the equipment is operated (Fig. 6). This lateral force is caused by the transfer of force from the gear to the rack.

Roller supports

Roller supports act as vertical and horizontal guides for the rack as it is operated (Fig. 6). Roller supports, unlike reaction rollers, do not resist large forces. They are simply guides which insure that the rack moves smoothly through the operation cycle.

Inspection Form With Comments

The following pages (Fig. 28) present Parts 1 and 2 of the inspection forms for the

rack assembly which contain the field inspection questions. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

Condition Index Rules

The following section contains the rules for calculating the individual CIs for the gear rack assembly distresses. Distress descriptions and example illustrations are also provided.

Noise, Jumping, and Vibration

See noise, jumping, and vibration for the exposed gear assembly (Chapter 4)

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Reduced Tooth Contact

See reduced tooth contact for the exposed gear assembly (Chapter 4)

Tooth Wear

See tooth wear for the exposed gear assembly (Chapter 4)

Damaged Teeth

See damaged teeth for the exposed gear assembly (Chapter 4)

Rack Attachment Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Gear/Rack Displacement

Definition and Causes: Excessive lateral movement between the gear and the rack may cause the contact between gear teeth and rack teeth to decrease. With decreased contact, the stress on the teeth may increase significantly. The wear which causes this problem can be

Part 1 Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which gate leaf or valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the rack during gate movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, and/or vibration is NORMAL.

The presence of CRACKS on the RACK is usually not tolerated. Record the NUMBER OF CRACKS found by visual observation. Many times a crack will show up as corrosion underneath the painted surface. Also record the LOCATION of the cracks.

Record the average percentage of TOOTH CONTACT in the 5 teeth with the least contact area. The contact area is usually associated with an area where the grease film is noticeably thinner. Wear patterns may also help to identify the contact area. Once the contact area has been identified, the % CONTACT is recorded as the percentage of the total tooth area which is contacted area. Also, record where the CONTACT area LOCATION is, relative to the total tooth area. In the TOOTH DIRECTION, the location is recorded as occurring primarily at the tip (T), middle (M), root (R), or any combination of the three (Fig. 15). In the LATERAL DIRECTION, the location is recorded as occurring primarily on the top(P), center (C), bottom(B) or any combination of the three (Fig. 15). On a vertical rack there are two possibilities. If the tooth direction is upstream-downstream, top is the left side of the rack when looking downstream. If the rack is rotated ninety degrees from the upstream-downstream position, top is defined as the side of the rack on the downstream side.

Pick the TOOTH with the worst WEAR and look at the wear at the pitch line. Record if there is TOOTH WEAR. If the pitch line is not scribed on the teeth, a good estimate of the pitch line location is slightly towards the tip from the mid-depth of the tooth. If tooth wear is visible, estimate the PERCENTAGE of TOOTH THICKNESS REDUCTION. The percentage of thickness reduction can be estimated a number of ways. One technique is to measure both a worn tooth and a tooth which has infrequent contact at the pitch line with a ruler or tape measure and compare the tooth thicknesses. A second technique to estimate the thickness reduction of tooth thickness on meshing gear and rack with different widths is to check for a worn ledge on the wider tooth, with the depth of the ledge being the estimate of reduction in thickness. If the estimated percentage is greater than 10%, record the MEASURED percentage using wear measurement techniques in Appendix B.

Pick the worst DAMAGED TOOTH for each type of damage on the rack and record the percentage of SURFACE AREA which is missing due to CHIPPING, DEFORMATION, PITTING, CORROSION, or GOUGING. If damage has occurred indicate the TYPE of DAMAGE. Chipping of the tooth is the breaking off of steel pieces, which usually results in

Part 1 Comments: Field data (continued)

jagged edges and high stress concentrations in the tooth. Deformation of the tooth is the changing of the shape of the tooth, usually the result of excessive forces or something becoming lodged in between teeth during operation. Pitting of the tooth is the severe localized corrosion of the tooth which results in small cavities in the tooth surface. Corrosion is the loss of steel in the tooth surface due to interaction with the environment.

Record the evidence of RACK ATTACHMENT DETERIORATION. Record whether there is any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE NUTS. If a sector gate is being inspected, the bolts attach the rack to the gate. If a miter lock gate or dam gate is being inspected, the bolts connect the rack to an I-beam.

Figure 28. (continued)

PART 2 Comments: Field data

Record whether the RACK BEING INSPECTED IS USED TO OPERATE A MITER LOCK GATE OR DAM GATE. If yes, the following questions should be answered.

Excessive lateral DISPLACEMENT of the ROLLER RACK is an indication that a problem is developing in the equipment. The movement can be quantified by placing permanent marks on the gear and rack (Fig. 29). The distance between these two points is recorded when the gear and rack are JACKED or pried APART and when JACKED or pried TOGETHER. The pry bar is placed between the gear and the rack to force the roller rack and gear apart and the first measurement is taken (Fig. 29). A jack can also be placed in a position to force the gear and roller rack apart. The second measurement is taken after the pry bar or jack are placed on the opposite side and used to force the gear and roller rack together. These measurements should be taken when the gate is OPEN and CLOSED. The difference between these two measurements indicates the "play" in the system. This measurement is not applicable to racks attached to sector gates.

Record the evidence of WEAR ON THE REACTION ROLLER EDGE of the rack. If there is wear, estimate the amount of wear to the nearest 1/16 in. Record the evidence of WEAR ON THE BOTTOM FLANGE of the rack. If there is wear, estimate the amount of wear to the nearest 1/16 in. Also record any evidence of BOW IN THE RACK.

Record whether the REACTION ROLLERS TURN FREELY by hand WHEN NOT IN CONTACT WITH the RACK. Indicate whether the reaction rollers WOBBLE. Also record if the reaction ROLLERS ARE CAUSING DAMAGE TO the RACK.

Record the evidence of MOVEMENT of the REACTION ROLLERS ANCHORAGE base as the gate is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement. A dial gage change greater than 0.002 in. is considered movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment. Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE NUTS at the reaction rollers anchorage if the BOLTS are EXPOSED.

FORCE TOGETHER

REFERENCE LINE

REACTION ROLLERS

PRY BAR

PERMANENT MARKS

PRY BAR

ROLLER RACK

MEASURED
DISTANCE

SECTOR
GEAR

FORCE
APART

PLAN VIEW

FIRST FORCE APART
THEN FORCE TOGETHER
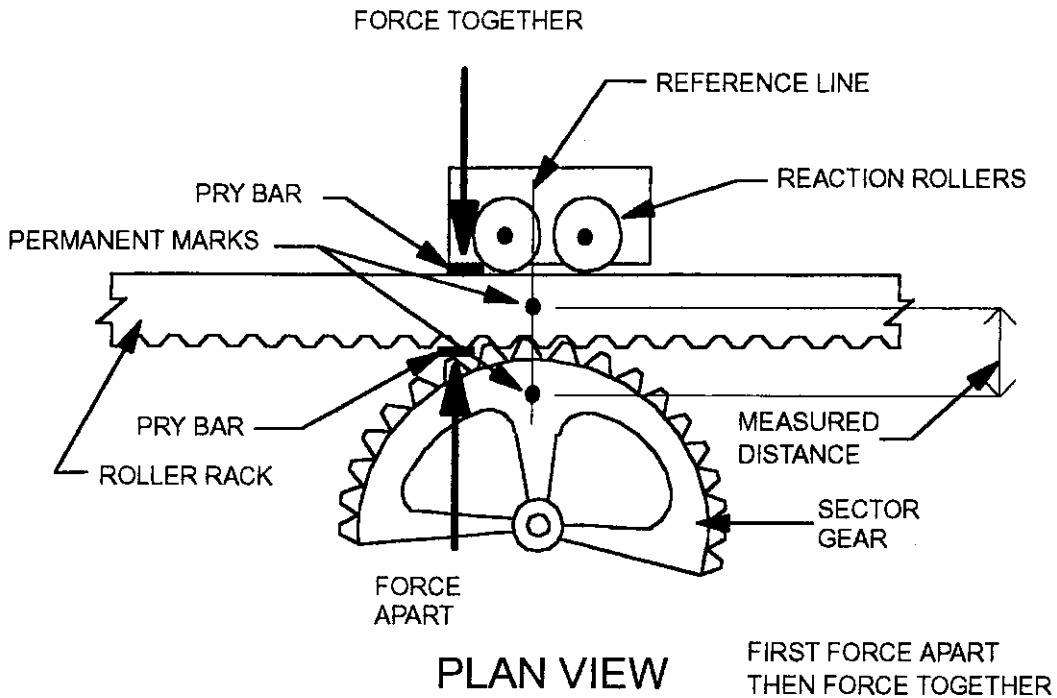
JACK OR PRY BAR
MAY BE USED

PRY BAR

ROLLER
RACK

SECTOR
GEAR

ANCHORAGE
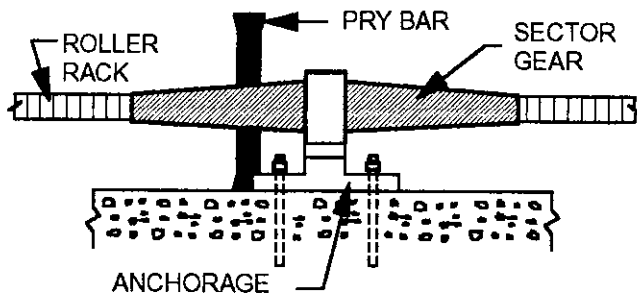
SECTION VIEW

Figure 29. Gear and Rack Displacement

due to improper lubrication, jumping, or vibration during operation of the assembly.

Measurement and Limits: Measurements are recorded when the rack is moved to the right and left with a crow bar (pinch bar) or a jack (Fig. 29).

X_1 = Measurement when jacked or pried apart

X_2 = Measurement when jacked or pried together

The X movement is taken as the difference between these two measurements.

$$X = \left| X_2 - X_1 \right| \qquad (6.1)$$

These measurements are taken twice, once with the gate opened and once with the gate closed and the largest X is used. The limiting value for this movement is taken as

$$X_{MAX} = \tfrac{1}{2} \text{ in.} \qquad (6.2)$$

Example: A gear and rack were pried apart. The measurement was

$$X_1 = 12.53 \text{ in.}$$

The assembly was then pried together. This measurement was

$$X_2 = 12.00 \text{ in.}$$

The displacement X is found by Equation 6.1.

$$X = \left| 12.53 - 12.0 \right| = 0.53$$

The CI for gear and rack displacement is

$$CI = [100(0.4)^{0.53/0.50}] = 38$$

The CI is rated poor.

Rack Wear

Definitions and Causes: Rack damage can be in the form of loss of steel section or bowing of the rack. The loss of section can occur both on the reaction roller edge and on the bottom flange of the rack. This wear is caused by interaction with the rollers. Bowing of the rack can occur from excessive force being applied to the rack.

Measurements and Limits: The amount of wear, X, on either the roller edge or bottom flange of the roller rack is recorded in the inspection form. The maximum of the two X values is used to calculate the CI. The limiting value for rack wear is

$$X_{MAX} = 1/8 \text{ in.} \tag{6.3}$$

If bowing in the rack is evident, the CI shall be 70.

The CI for rack wear is the minimum of the CIs for wear and for bowing of the rack.

Example: Wear on the bottom flange of a rack was

$$X = 1/16 \text{ in.}$$

There was no noticeable wear on the reaction roller edge nor was there any bowing of the rack. The CI for rack wear is

$$CI = [100(0.4)^{(1/16)/(1/8)}] = 63$$

The CI is rated fair.

Reaction Rollers Wear/Damage

Definitions and Causes: The bushings or bearings in reaction rollers can freeze and stop rotating or in some cases wear and cause the rollers to wobble. Inadequate lubrication and interaction with the environment can cause seizing of the bushings or bearings. Wobble in the reaction rollers can be caused by regular use or inadequate lubrication.

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Measurements and Limits: The reaction rollers are checked to see if they rotate freely when they are not in contact with the rack. If they do not rotate freely, the CI for reaction rollers is 70. The rollers are also observed to see if they wobble. If they wobble, the CI is 70. If the rollers are causing damage to the rack the CI is 40.

Example: Wobble was observed in a reaction roller; therefore,

$$CI = 70$$

The CI is rated good.

Reaction Roller Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the gear rack assembly is the crack distress. The CIs from the remaining distresses will be used to calculate the weighted assembly CI_w (Equation 2.5). For a rack used to operate a sector lock gate, five distresses will be used to calculate the weighted assembly CI_w. The weighting factors for those distresses are found in Table 15. For a rack used to operate a miter lock gate or a dam gate, eight distresses will be used to calculate the weighted assembly CI_w. The weighting factors for those eight distresses are in Table 16.

Field Test

The bar charts in Figure 30 and 31 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective condition index during the field tests to the
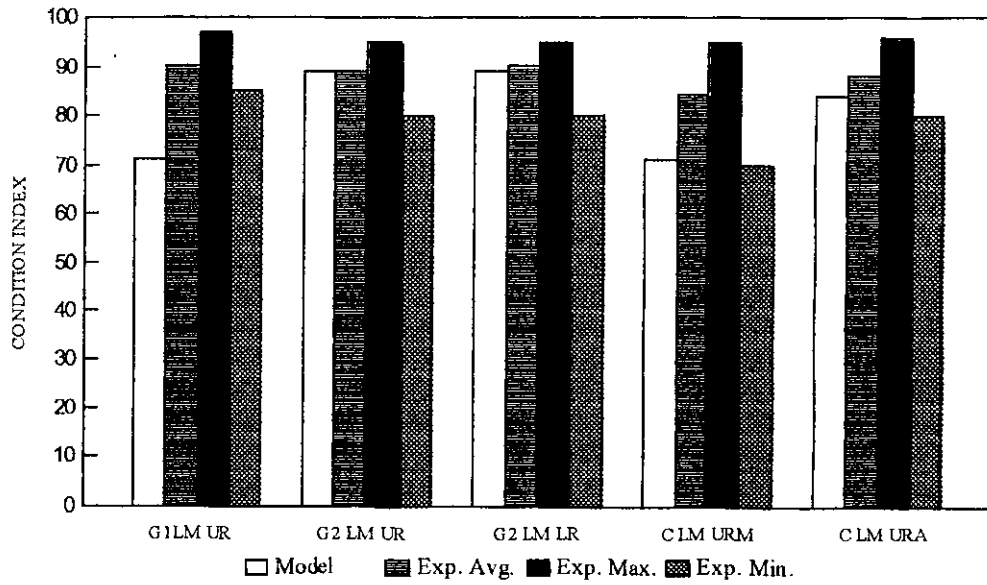
Figure 30. Reduced Tooth Contact: Gear Rack Assembly
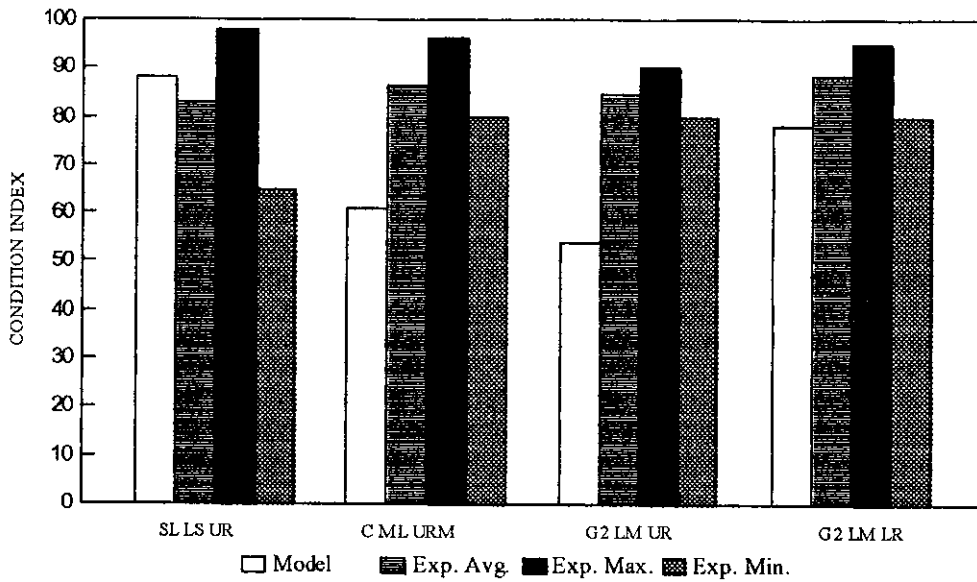
Figure 31. Gear/Rack Displacement: Gear Rack Assembly

condition index calculated from the rules for two rack distresses. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts' condition indexes are summarized below.

Noise, Jumping, and Vibration

Because no abnormal noise, jumping, or vibration was recorded, the calculated CI values were 100. Although this distress was not recorded, the experts' average was below 90 on three of seven assemblies which were rated. However, in each of these three cases the experts' average was 85 or greater. The noise, jumping, and vibration distress was calibrated in Chapter 5 for the enclosed gear assembly.

Cracks

The cracks distress was not calibrated because there were no cracks observed in sector gears or racks. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above. Although this distress was not calibrated the experts feel that cracks in the gear or rack are critical and should be repaired, which corresponds well to the rules for the gear rack assembly.

Reduced Tooth Contact (Fig. 30):

The tooth contact distress and tooth wear distress were initially combined as one distress. Discussion with the experts near the end of the Louisville District field test resulted in separating the original distress into two distinct distresses - tooth contact and tooth wear. Although no data was collected after the separation of the distresses, the data collected for the original combined distress was used to calibrate the tooth contact distress. The authors feel this is appropriate for two reasons: 1) the observed wear of the rack teeth was relatively low on

the observed gears and 2) the weighting factor for tooth contact was significantly higher than the weighting factor for tooth wear (Table 15, 16). In two cases where the tooth contact/wear distress was observed (Miter Lock Gate Upper Right Cannelton and Miter Gate Upper Right Green River #2), the calculated CIs were lower than the experts' average CIs. In these cases the calculated CIs were in Zone 2. In the other two cases, the calculated CIs corresponded well with the expert average CIs.

Tooth Wear

Discussion with the experts near the end of the Louisville District field test resulted in a separation of the tooth wear and tooth contact distresses (see previous distress). Therefore, while the tooth wear distress was observed, calibration of the new rules is not possible with the current data, which was used in the calibration of the tooth contact distress. The new rules for tooth wear have, however, been constructed using the experts' judgement and advice.

Damaged Teeth

The damaged teeth distress was not calibrated because there were no damaged teeth observed in the racks. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above. While the damaged gear teeth distress was not calibrated for the rack assembly, the same distress was calibrated for the enclosed gear assembly (Chapter 5).

Rack Attachment Deterioration

The rack attachment deterioration distress was not calibrated because no deterioration was observed in the rack attachment for sector gates. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above. While the rack attachment deterioration distress was not calibrated for the rack assembly, the anchorage movement/deterioration

distress was calibrated for the exposed gear assembly (Chapter 4) and the enclosed gear assembly (Chapter 5).

Gear/Rack Displacement (Fig. 31):

The calculated CIs were within 9 points of the experts' average CIs on all but two (Upper Right Lock Gate Green River 1 and Upper Right Lock Gate Main Chamber Cannelton) of the sector gear and rack assemblies which were rated. In both of these cases the measured displacement was 3/16 inches, which were the largest displacements observed during the field tests. In both cases the calculated CI was well below the experts' average CI. In each of the other sector gear and rack assemblies where the displacements were smaller, the calculated CIs were in better agreement with the experts' averages.

Rack Wear

The rack wear distress was not calibrated because rack wear was not observed during the field tests. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above.

Reaction Rollers Wear/Damage:

The reaction rollers wear/damage distress was not calibrated because the distress was not observed during the field tests. Hence, the calculated CIs were all 100. The experts' averaged CIs ranged between 83 and 92. The experts were reluctant to rate the reaction rollers higher because they were not in perfect working condition. Although the reaction rollers did turn freely when not loaded, they were no longer in the condition they had been in when installed.

Reaction Roller Anchorage Movement/Deterioration

The reaction roller anchorage movement/deterioration distress was not calibrated

because no movement or deterioration of the anchorage was observed. Hence, the calculated

CIs were all 100 and the experts' averaged CIs were 90 or above. While the reaction roller

anchorage movement/deterioration distress was not calibrated for the rack assembly, a similar

distress was calibrated for the exposed gear assembly (Chapter 4) and the enclosed gear

assembly (Chapter 5).

Assembly CI (Fig. 32):

The assembly CI for the rack assembly was calibrated for three assemblies. In each

case the model CI was slightly higher than the experts' average CI. Although the model CIs

were higher, the experts' average CIs and the model CIs were all in the upper part of Zone 1.
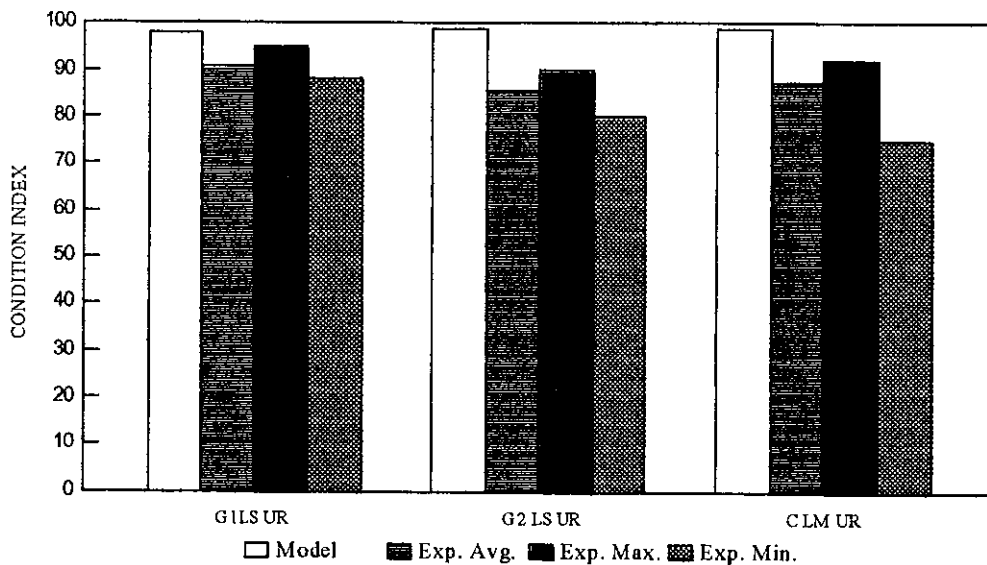
Figure 32. Gear Rack Assembly CI

CHAPTER 7. STRUT ARM ASSEMBLY

Component Identification

Definitions and sketches for components of the strut arm assembly are presented in the following paragraphs.

Strut

The strut transfers force from one component to another. Its function when used with a lock gate is to transfer force from the sector arm to the gate (Fig. 6). The strut transfers force from the rocker arm assembly to the valve when used with a valve structure (Fig. 8).

Linkage pin

The linkage pin serves as a pivot point for the strut (Fig. 6). For lock gates, one linkage pin serves as a pivot between the sector arm and the strut and a second pin serves as a pivot between the strut and the gate. Valve struts also have pins on both ends.

Compression spring

The compression spring is located in the strut (Fig. 6, 8). Its function is to allow the strut to shorten or lengthen slightly when the gates or valves are closed or lowered. This provides a tight fit without damaging the structure. The compression spring also acts as a shock absorber between the gate and the operating equipment.

End Connection

The end connection is fixed to the gate, sector arm, or valve and transfers force from the strut to these structures or components (Fig. 8).

Inspection Form With Comments

The following page (Fig. 33) presents the inspection form for the strut arm assembly which contains the field inspection questions. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

Condition Index Rules

The following section contains the rules for calculating the individual CIs for the strut arm assembly distresses. Distress descriptions and example illustrations are also provided.

Noise, Jumping, Vibration

See noise, jumping, vibration for the exposed gear assembly (Chapter 4)

End Connection Movement

Definition and Causes: The strut arms are connected to the sector gear or valve with linkage pins. Over time, the pins and bushings wear due to normal operation or improper lubrication. Relative movement is experienced due to the wear in the linkage pins and the bushings. In some cases, the connection is designed without a bushing. In this case the wear occurs directly between the pin and the strut arm.

Measurement and Limits: End connection movement at the opened and closed positions is visually observed and recorded to the nearest eighth of an inch. The X value for end connection movement is the relative movement between the end of the strut and the structure to which it is attached. The greater of X_1 and X_2 at the two ends of the strut arm is used to calculate the CI.

$$X = Maximum\ (X1,\ X2) \tag{7.1}$$

Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify whether a lock gate, valve, or dam gate is being inspected. Also enter the power transfer number(P.T.#) which can be found on Page 1 of the inspection form.

Observation of the strut arm assembly during gate and valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, vibration is NORMAL.

Record the relative MOVEMENT in the END CONNECTION between the strut arm and the attached component or structure. Estimate the movement to the nearest 1/8 inch. To further enhance the visual observation, one can place a dial gage at this location. Record the readings while the operating equipment is in the OPEN and CLOSED positions. Movement should be recorded for both ends of the strut arm (Fig. 34), both at the POWER END and at the OTHER END. The END CONNECTION MOVEMENT at the bottom of the valve strut is inspected during the valve inspection (leave OTHER END blank).

Record if the COMPRESSION SPRING is operating normally. Watch the structure as it is opened and closed. The spring should MOVE FREELY at the beginning and end of the stroke. During the closing of the structure the compression spring should compress at least ½ to 1 in. and should release when the force in the strut changes from compression to tension. The compression spring should act as a shock absorber to soften the loads transmitted to the operating machinery. If the compression spring does not move freely, record whether LACK OF MOVEMENT COULD CAUSE DAMAGE to EQUIPMENT or to the structure.

The presence of excessive CORROSION on the strut arm is a potential problem. Record the WALL THICKNESS of the STRUT in order to better judge the corrosion. Obtain the wall thickness from construction drawings. Record YES if there is SIGNIFICANT CORROSION (more than general scaling). If yes, indicate if there is SEVERE PITTING (1/8 inch pits or greater) in a dense pattern or GENERAL THICKNESS REDUCTION of 10% or greater in local areas.

The presence of CRACKS on the strut arm is usually not tolerated. Record the NUMBER OF CRACKS found on these components by visual observation as well as the LOCATION of the cracks with respect to the POWER END.

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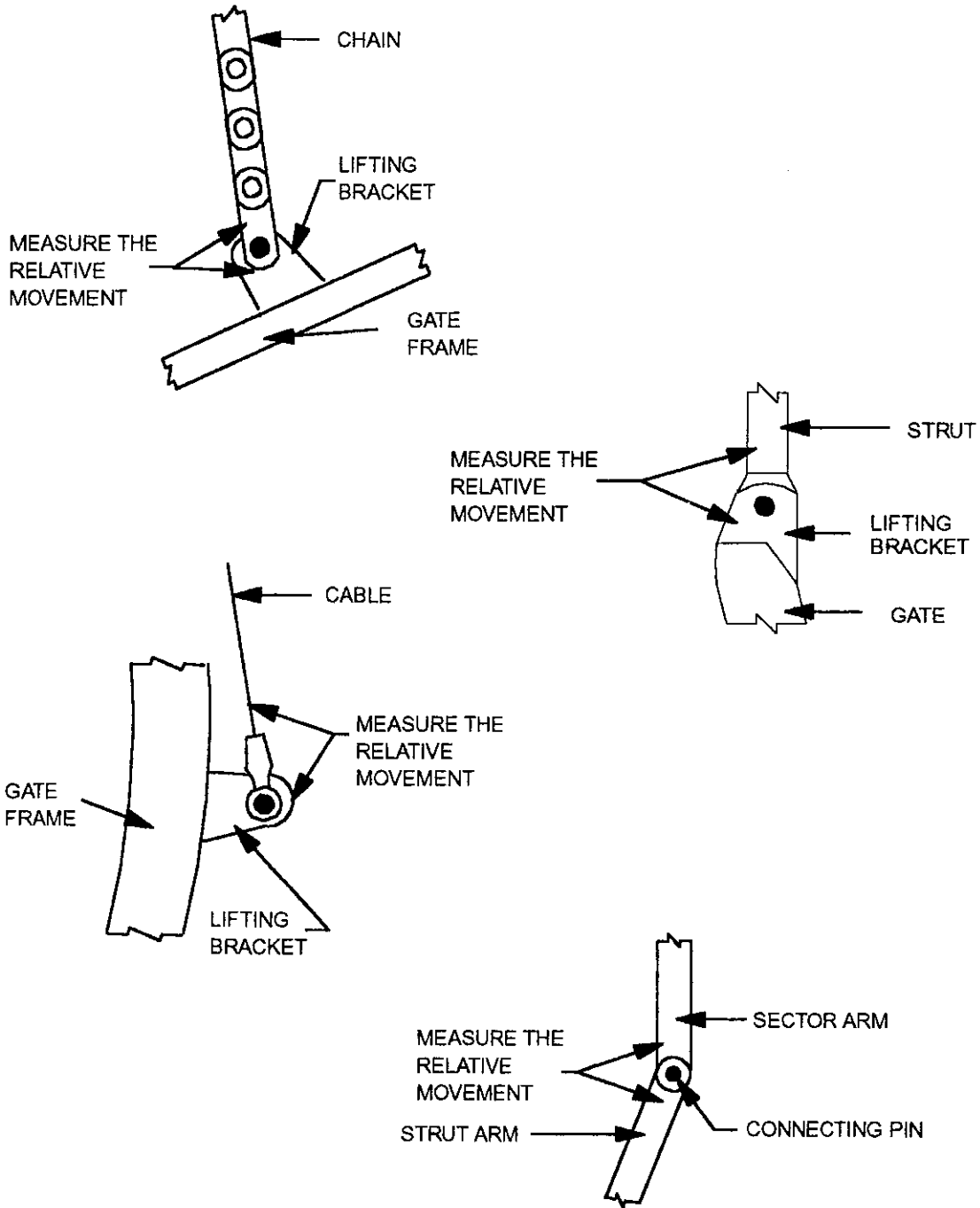
Figure 34. End Connection Movement Distress

For valves the end of the strut arm connected to the valve is inspected during the valve inspection, in which case X is equal to the measurement at the power end. The limiting value for end connection movement is

$$X_{MAX} = 1/4 \text{ in.} \tag{7.2}$$

Example: The relative movement of the strut arm end connection at End 1 was

$$X_1 = 1/8 \text{ in.}$$

and at End 2 was

$$X_2 = 1/4 \text{ in.}$$

The value of X by Equation 8.1 is

$$X = Maximum(1/8, 1/4) = 1/4 \text{ in.}$$

The CI for the strut arm end connection movement is

$$CI = [100(0.4)^{(1/4)/(1/4)}] = 40$$

The CI is rated marginal.

Compression Spring Movement

Definition and Causes: The compression spring acts like a shock absorber as the gate opens into the recess or closes for emptying or filling of the chamber. Normal compression spring movement occurs near the end of the opening and closing cycles. Corrosion or other damage can cause the compression spring to lose flexibility.

Measurement and Limits: If the compression spring is not working properly, but will not likely damage the other operating equipment, the CI is 70. If, however, the compression spring is not working properly and could cause damage to the structure and other operating equipment, the CI is 40.

Example: A compression spring did not move during the opening and closing of a lock gate. The lack of movement created the potential for damage to occur to other operating equipment. The CI for the compression spring is

$$CI = 40$$

The CI is rated marginal.

Corrosion

Definitions and Causes: Corrosion involves the loss of steel material on the strut arm assembly due to interaction with the environment. If this interaction continues, pitting occurs. Pitting is the minor loss of steel in localized areas. While light deterioration causes little structural problems, extensive corrosion can reduce the cross-sectional area of the assembly thereby increasing the stresses.

Measurements and Limits: Corrosion that is more intensive than general scaling is recorded. If there is corrosion greater than scaling but pitting is less than 1/8 inch and general thickness reductions are less than 10%, the CI is 70. If there is pitting of 1/8 inch or greater or a general thickness reduction of 10% or greater , the CI should be reduced to 40. Example: Corrosion of a strut arm was detected during an inspection. In several local areas the general thickness reduction of the arm was 15% of its original thickness. The CI for corrosion is

$$CI = 40$$

The CI is considered marginal.

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the strut assembly is the crack distress. The CIs from the remaining four distresses will be used to calculate the weighted CI_w (Equation 2.5). The weighting factors for those four distresses can be found in Table 17.

Field Test

The bar charts in Figures 35 and 36 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective condition index from the field tests to the condition index calculated from the rules for two strut arm distresses. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts' condition indexes are summarized below.

Noise, Jumping, Vibration

The noise, jumping, and vibration distress was not calibrated because the distress was not observed in strut arms. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or above. The noise, jumping, and vibration distress was, however, calibrated for the enclosed gear assembly.

End Connection Movement (Fig. 35):

For the four strut arms for which movement was observed (Newburgh Upper Right Miter Lock Gate, Green River #2 Lower Right Miter Lock Gate, Cannelton Upper Right Miter Lock Gate, and Cannelton Upper Left Miter Lock Gate) the calculated CIs were no
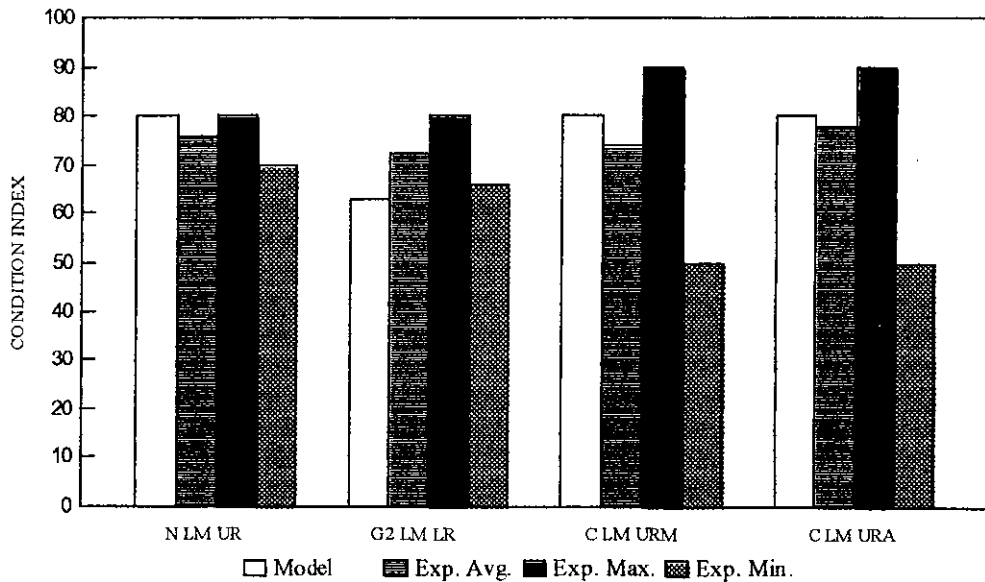
110

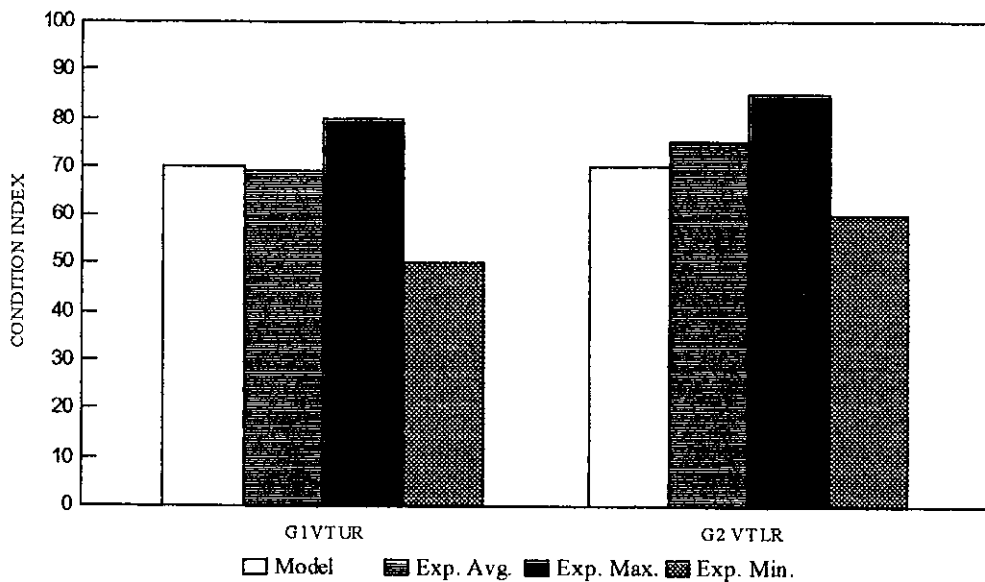**Figure 35. End Connection Movement: Strut Arm Assembly**

Figure 36. Corrosion: Strut Arm Assembly

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more than 9 points from the experts average CIs.

Compression Spring Movement

The compression spring movement distress was not calibrated because no compression spring movement problems in strut arms were observed. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or above.

Corrosion (Fig. 36):

The calculated CIs was within 5 points of the experts' average CIs for corrosion of the strut arms at the two locations (Green River #1 Right Filling Valve and Green River #2 Right Emptying Valve) where the corrosion distress was observed. Both of these struts were valve operating equipment. The corrosion distress for struts was not observed on any struts used to operate miter lock gates.

Cracks

The cracks distress was not calibrated because no cracks in strut arms were observed. Hence, the calculated CIs were all 100 and the experts' average condition indexes were 90 or above. Although this distress was not calibrated the experts feel that cracks in the strut are critical and should be repaired, which corresponds well to the rules for strut arms.

Assembly CI (Fig. 37):

The assembly CI for strut arms was calibrated for six assemblies. In each case the model CI was higher than the experts' average CI. Although the model CIs were higher, the experts' average CIs and the model CIs were all in zone 1.
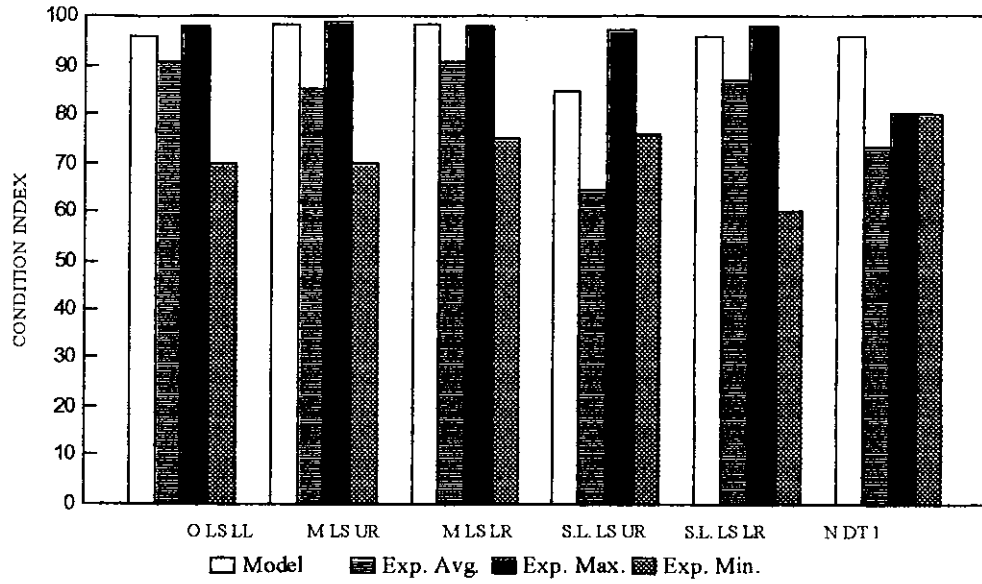
Figure 37. Strut Arm Assembly CI

CHAPTER 8. ROCKER ARM ASSEMBLY

Component Identification

Definitions and sketches for components of the rocker arm assembly are presented in the following paragraphs.

Rocker

The rocker consists of steel arms which are joined with connecting pins (Fig. 8). It transfers and redirects the horizontal load produced by a hydraulic cylinder to a vertical strut arm assembly.

Pivot point

The pivot point is the connecting pin on which the rocker rotates (Fig. 8).

Connecting rod

The connecting rod transfers force from the piston rod to the rocker (Fig. 8). Not all rocker assemblies have connecting rods.

Inspection Form With Comments

The following page (Fig. 38) presents the inspection form page for the rocker arm assembly which contains the field inspection questions. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

Condition Index

The following section contains the rules for calculating the individual CIs for the rocker arm assembly distresses. Distress descriptions and example illustrations are also provided.

Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the rocker arm during gate movement is a good indicator of problems. Record any indication NOISE, sudden JUMPING, and/or VIBRATION during operation. Also indicate whether this noise, jumping, and/or vibration is NORMAL.

Record any evidence of MOVEMENT at the ANCHORAGE of the PIVOT POINT as the valve is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement (Fig. 39). A dial gage change greater than 0.002 in. is considered movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment. Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN. or LOOSE nuts at this connection if the BOLTS are EXPOSED.

Record the relative MOVEMENT at the PIVOT POINT PIN (Fig. 39) between the rocker and the anchorage bracket by visual observation to the nearest eighth of an inch. To further enhance the visual observation, one can place a dial gage at this location.

Record the relative CONNECTION MOVEMENT between the ROCKER AND CONNECTING ROD (Fig. 39) by visual observation to the nearest eighth of an inch. To further enhance the visual observation, one can place a dial gage at this location.

The presence of excessive CORROSION on the rocker arm or connecting rod is a potential problem. Select the section of the rocker arm or connecting arm with the most corrosion. From construction drawings, record the NEW SECTION THICKNESS at this location. Record YES if there is SIGNIFICANT CORROSION(more than general scaling). If yes, indicate if there is SEVERE PITTING (1/8 inch pits or greater) in a dense pattern or GENERAL THICKNESS REDUCTION of 10 % or greater in local areas.

The presence of CRACKS on the rocker arm assembly is usually not tolerated. Record the NUMBER OF CRACKS found on the rocker and connecting rod by visual observation. Many times a crack will show up as corrosion underneath the painted surface. Also record the LOCATION of any cracks.

Note: Wear at the connection of the rocker to the strut is recorded in the STRUT inspection and wear at the connection of the rocker to the piston rod is recorded in the HYDRAULIC CYLINDER inspection.

CYLINDER END CONNECTION PIN

DIAL GAGE

PISTON ROD

CONNECTING ROD

CONNECTING PIN BETWEEN
CONNECTING ROD
AND ROCKER ARM

PIVOT POINT
ANCHORAGE

PIVOT POINT PIN

CONNECTION PIN TO STRUT

STRUT

TO VALVE
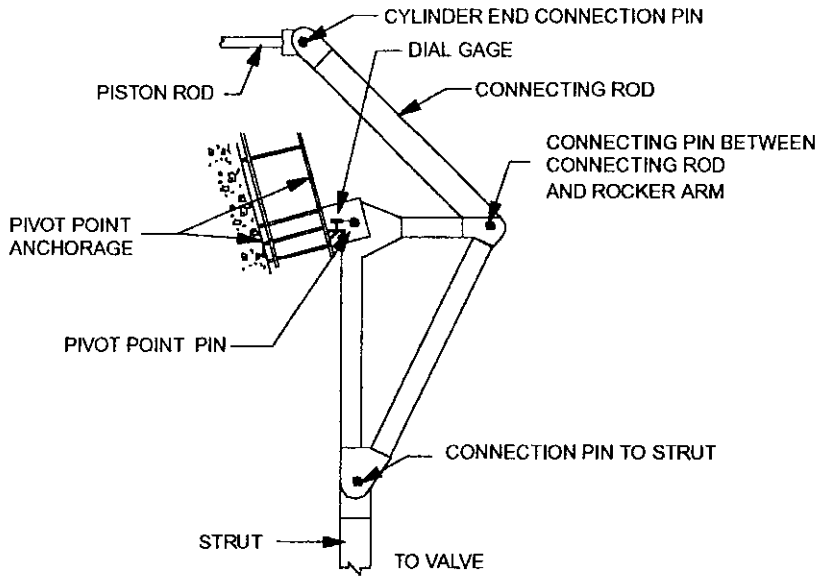
Figure 39. Rocker Arm Distress Measurements

Condition Index

Noise, Jumping, Vibration

See noise, jumping, vibration for the exposed gear assembly (Chapter 4)

Pivot Point Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Pivot Point Pin Movement

See end connection movement for the strut arm assembly (Chapter 7)

Rocker And Connecting Rod Connection Movement

See end connection movement for the strut arm assembly (Chapter 7)

Corrosion

See corrosion for the strut arm assembly (Chapter 7)

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the rocker arm assembly is the crack distress. The CIs from the remaining five distresses will be used to calculate the weighted CI_w (Equation 2.5). The weighting factors for those five distresses can be found in Table 18.

Field Tests

The bar charts in Figures 40 and 41 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective condition index from the field tests to the condition index calculated from the rules for two rocker arm distresses. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts' condition indexes are summarized below.

Noise, Jumping, Vibration

The noise, jumping, and vibration distress was not calibrated because no noise, jump, or vibration in rocker arms was observed. Hence, the calculated CIs were all 100 and the experts' average condition indexes were 90 or above. The noise, jumping, and vibration distress was calibrated in the enclosed gear assembly and the calculated CIs closely approximated the experts' averages.

Pivot Point Anchorage Movement/Deterioration (Fig. 40):

The pivot point anchorage movement/deterioration distress was observed on a filling valve at Green River #1 Lock. The experts' average was 15 points higher than the calculated
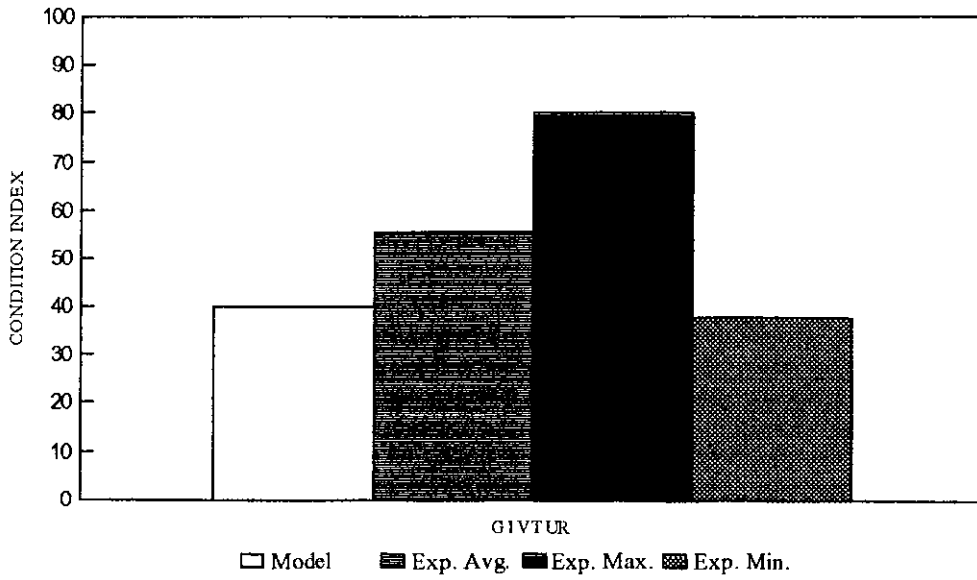
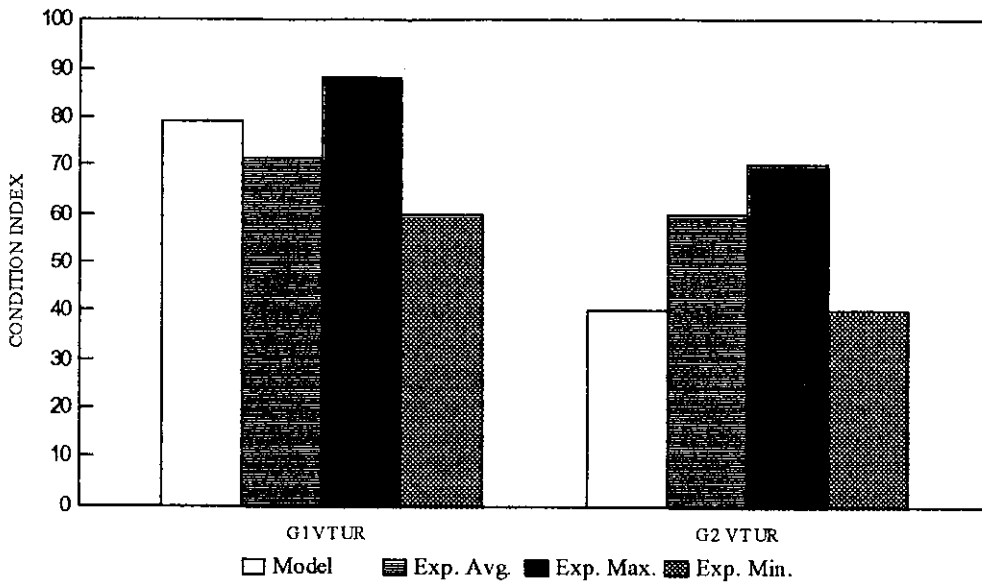**Figure 40. Pivot Point Anchorage Movement/Deterioration: Rocker Arm Assembly**

Figure 41. Pivot Point Pin Movement: Rocker Arm Assembly

CI of 40.

Pivot Point Pin Movement (Fig. 41):

The pivot point pin movement distress was observed at two locations. At one location (Green River #1) the movement was 1/16 inch and the calculated CI was 7 points from the experts' average. Although the movement was four times larger at the second location (1/4 inch at Green River #2), the experts' lowered their average by only 12 points, from 72 to 60. The calculated CI at the second location decreased by 39 points and was equal to the expert low (40).

Movement Between Rocker And Connecting Rod

The movement between rocker and connecting rod distress was not calibrated because no relative movement between the rocker and the connecting rod in rocker arms was observed. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or above.

Corrosion

The corrosion distress was not calibrated because no significant corrosion in rocker arms was observed. Hence, the calculated CIs were all 100 and the experts' average condition indexes were 90 or above. The rule for the corrosion distress was, however, calibrated for strut arms.

Cracks

The cracks distress was not calibrated because no cracks in rocker arms were observed. Hence, the calculated CIs were all 100 and the experts' average condition indexes were 90 or above. Although this distress was not calibrated the experts feel that cracks in the

rocker arm are critical and should be repaired, which corresponds well to rules for rocker arms.

Assembly CI (Fig. 42):

The assembly CI for rocker arms was calibrated for two assemblies. The model CI was slightly lower than the experts' average CI for the case in zone 2 (Upper Right Valve Green River #1), and was higher than the experts' average CI for the case in zone 1 (Lower Right Valve Green River #2).
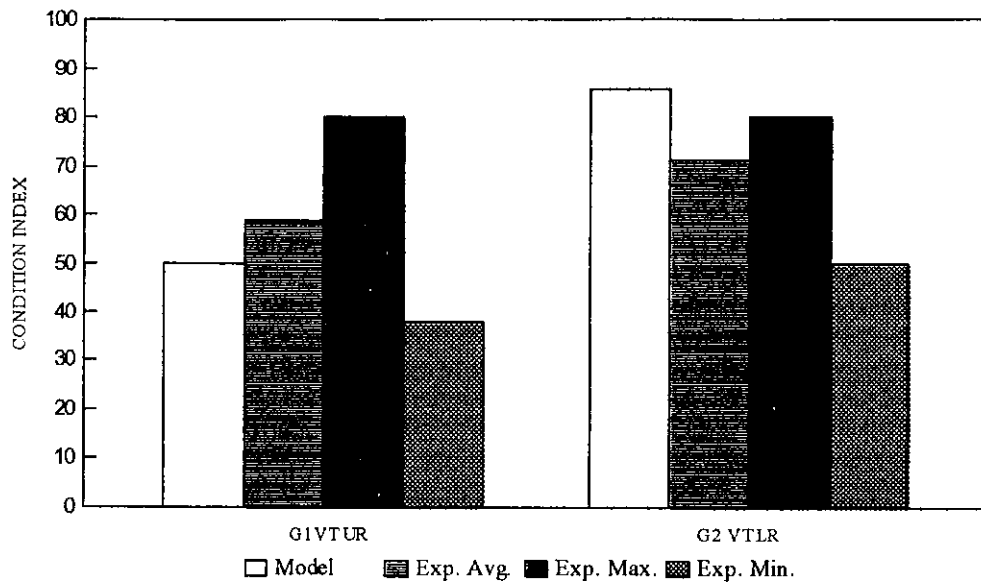
Figure 42. Rocker Arm Assembly CI

CHAPTER 9. CABLE ASSEMBLY

Component Identification

Definitions and sketches for components of the cable assembly are presented in the following paragraphs. Cable lifting systems are sometimes used to raise and lower or open and close the structures (Fig. 43, 44, 45).

Cable (wire rope)

The cable is made up of several strands (Fig. 46). Cable is usually wound in one of two ways: regular or lang lay. The wires of a regular lay are twisted to make the strands, and the strands are then twisted in the opposite direction to make the rope. The wires in the regular lay end up running in the longitudinal direction. In the lang lay, the wires and strands are twisted in the same direction. Figure 46 shows a lang lay [28].

LOCK CHAMBER
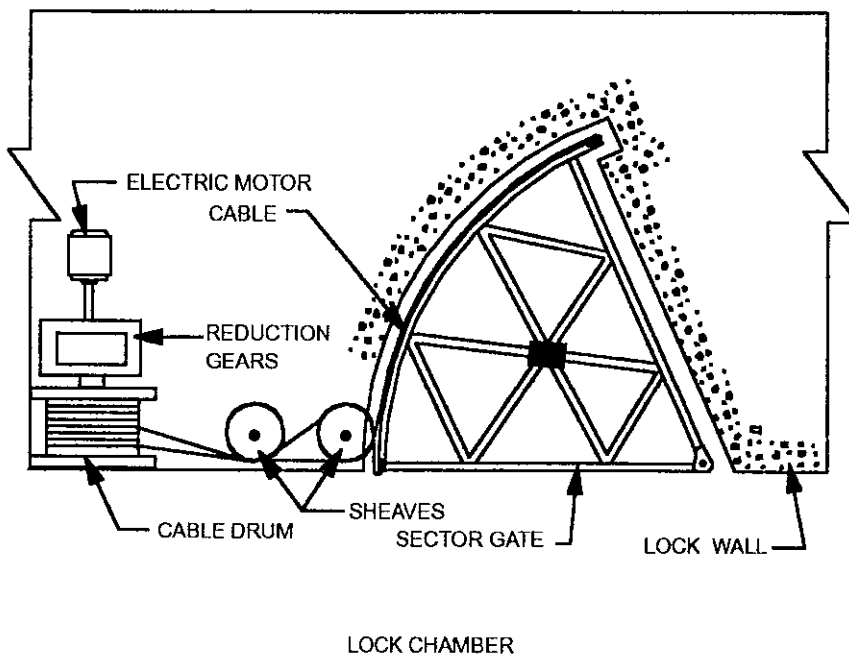
Figure 43. Plan View of Sector Lock Gate Operating Equipment (Cable)
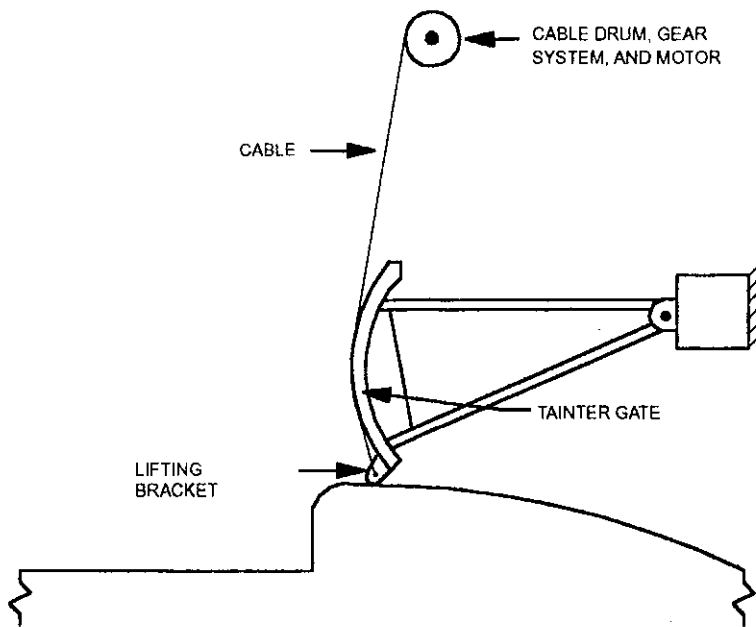
Figure 44. Side View of Tainter Dam Gate Operating Equipment

Cable Strand

The cable strand is made up of several wires, wrapped together in various arrangements (Fig. 46).

Cable Wire

The smallest component of the cable is the single steel wire (Fig. 46).

Cable Lay

The cable lay is the length of cable in which a strand makes one complete revolution of the cable (Fig. 46).

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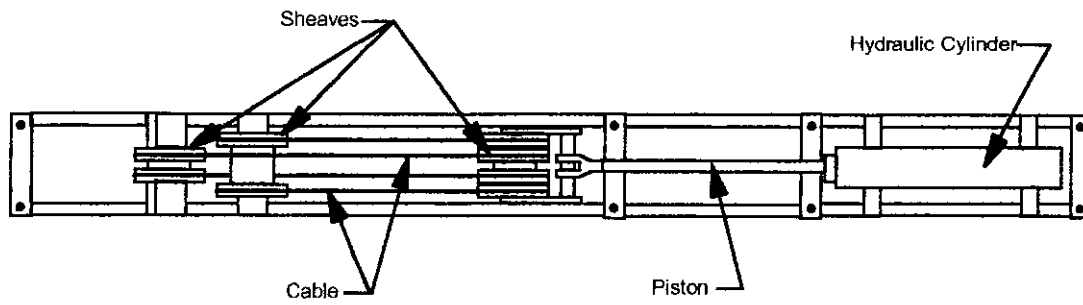
Plan View
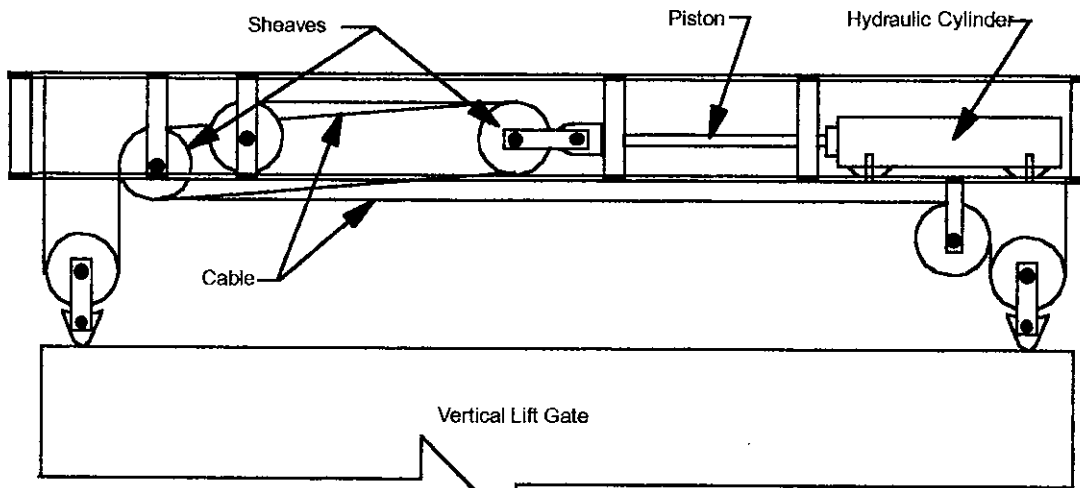
Elevation View

Figure 45. Vertical Lift Gate Operating Equipment
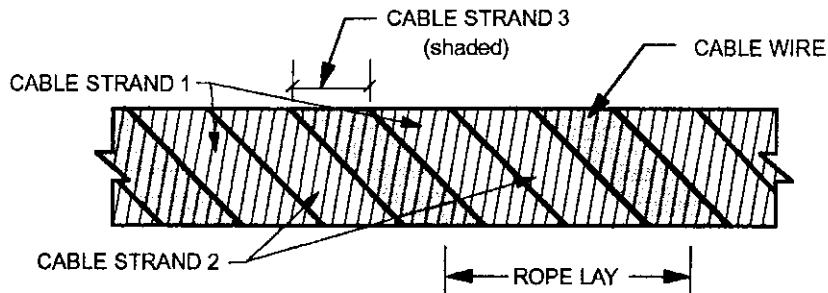
Figure 46. Cable Schematic

Cable Drum

The cable drum is the component around which the cable is wound as the valve structure is raised and lowered or the gate is moved (Fig. 43, 47).

Sheave

The sheave is a wheel with a grooved rim. It is used to redirect the cable (Fig. 43, 45).

Idler/Roller

The idler, or roller, is a pulley used to guide and take up slack in the cable.

Inspection Form With Comments

The following pages (Fig. 48) present Parts 1, 2, and 3 of the field inspection forms for a cable assembly. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).
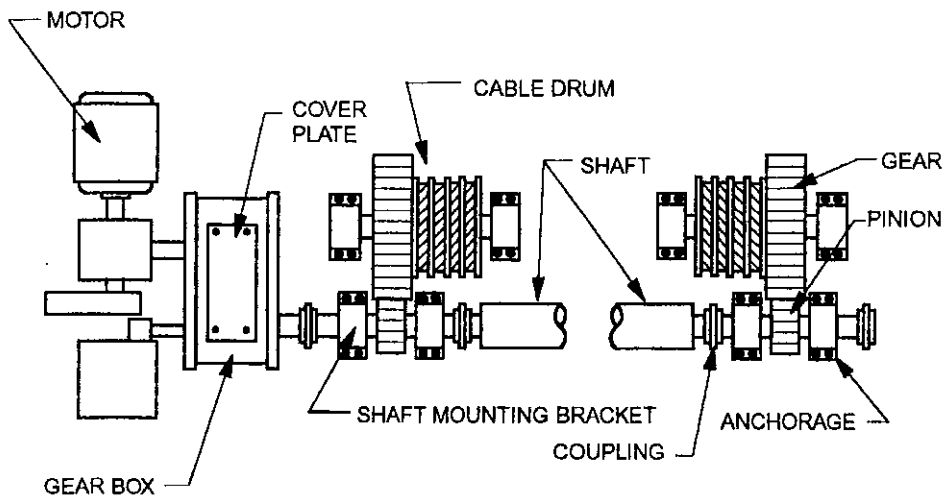
Figure 47. Plan View of Tainter Gate Operating Equipment

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Part 1 Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which gate or valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Indicate the NUMBER OF CABLES IN THE CABLE SET.

Observation of the cable assembly during gate and valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during the operation of the structure. Also indicate whether this noise, jumping, and/or vibration is NORMAL.

Record if a WORN PORTION of the outer cable WIRES is evident. If there is evidence of wear, record the average PERCENTAGE of WEAR of the wire diameter on the outer wires. The wear would most likely occur near the drum when the gate is in the opened or closed position. Also indicate the LOCATION of the worn section from the power end (Fig. 49).

Record if a REDUCTION IN ROPE DIAMETER of the cable is evident. If there is evidence of a reduced diameter, record the NEW DIAMETER and the smallest REDUCED DIAMETER. Look closely at the cable which is near the drum when the gate is in the opened or closed position. The reduction in area of the cable would most likely occur at the point of smallest radius of cable bend. The reduced diameter of the cable can often be checked with cable templates or with the use of calipers. Indicate the LOCATION of the reduced area from the power end (Fig. 49).

In steel cables, CORROSION of interior wires in the cable regularly occurs but is difficult to identify. Record any evidence of corrosion such as local discoloring or pitting of the wires. The splash zone is often a problem spot. Indicate whether the corrosion is SLIGHT (slight discoloration) or SEVERE (pitting and/or severe rusting). Indicate the LOCATION from the power end where the corrosion occurs (Fig. 49). Record whether the CABLE is LUBRICATED PROPERLY. Indicate the type of cable (CARBON STEEL,GALVANIZED, OR STAINLESS). Also record the number of YEARS SINCE the cable has LAST been REPLACED.

Part 2 Comments: Field data

A BIRD CAGE is a local area of unraveled portion of the cable (Fig. 50). Record the existence of BIRD CAGES, KINKS, OR PROTRUDING CORES (Fig. 51) on the inspection form. Indicate the type of distress (a bird cage, a kink, or a protruding core) if one of the three exists. Also record the LOCATION from the power end that this distress occurs (Fig. 49).

Record any existence of UNLAYED cable STRANDS. Unlayed strands occur when the cable rubs against an object. Unlayed strands are the strands displaced from the uniformly distributed manufactured position. Also indicate the LOCATION of the unlayed strands from the power end (Fig. 49).

Record the maximum number of BROKEN WIRES in all strands of any ONE ROPE LAY (Fig. 46). Also indicate the LOCATION of the broken wires from the power end of the cable (Fig. 49).

For cable sets with more than one cable, observe the cable and indicate if UNEQUAL TENSION occurs in each CABLE. Cable tension can be tested by applying equal force perpendicular to the length of each cable and observing the displacement of the cable in the direction of the force. The displacements should be equal if the cable tension is equal. Cable tension can also be tested by observing the vibration in each cable as wind or other disturbance vibrates the cable. If the cable tension for a cable is unequal, the vibrations in the cables could occur at different frequencies. The tension can also be tested by striking each cable separately and listening to the frequency of each cable. Cables with equal tension will have the same frequency. Also record the NUMBER of CABLES which have no or little tension.

For DRUMS, record if there is VISIBLE GROOVE WEAR. Groove wear is the wearing of the bottom of the grooves. If there is groove wear, estimate the DEPTH OF the GROOVE WEAR in percentage of the CABLE DIAMETER. If the estimate of groove wear is GREATER THAN 10% of the cable diameter, use an appropriate method to MEASURE the groove wear. Groove wear can be measured by placing a cable groove template into the groove and observing the gap between the bottom of the groove and the template. A similar procedure which can be used is to place a piece of new cable into the groove and measuring the gap. Indicate whether there is SIDE WEAR on the drum. If the cable is misaligned the guide plates will show the imprint of the cable (Fig. 52).

Record any evidence of MOVEMENT at the DRUM ANCHORAGE as the gate or valve is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement. A dial gage change greater than 0.002 in. is considered movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment. Small hairline

Part 2 Comments: Field data (continued)

cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE nuts at this connection if the BOLTS are EXPOSED.

The FOLLOWING QUESTIONS ON SHEAVES should be answered only if there ARE SHEAVES IN THE CABLE ASSEMBLY.

Record if there is VISIBLE GROOVE WEAR. Groove wear is the wearing of the bottom of the grooves. If there is groove wear, estimate the DEPTH OF the WORN GROOVE in percentage of the CABLE DIAMETER. If the estimate of groove wear is GREATER THAN 10% of the cable diameter, use an appropriate method to MEASURE the groove wear. Groove wear can be measured by placing a cable groove template into the groove and observing the gap between the bottom of the groove and the template. A similar procedure which can be used is to place a new cable into the groove and measuring the gap. Also indicate whether there is SIDE WEAR on the sheave.

Record if there is SHEAVE BEARING/BUSHING WEAR. Bearing and bushing wear can be observed by placing a pry bar between the sheave and a solid surface or watching the sheave during operation and checking for WOBBLE. Also record the LATERAL DISPLACEMENT observed when PRYING the SHEAVE.

Figure 48. (continued)

Part 3 Comments: Field data

Record any evidence of MOVEMENT greater than 0.002 at the SHEAVE ANCHORAGE as
the gate is opened and closed. Evidence of movement can be observed visually or enhanced
by placing a dial gage to monitor any movement. Excessive concrete spalling may indicate a
displacement occurred at this location at some time. Also, record the presence of any
CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the
interface of the embedment. Small hairline cracks, probably caused by thermal expansion or
contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10%
volume loss), MISSING OR BROKEN, or LOOSE nuts at this connection if the BOLTS are
EXPOSED.

Record whether there ARE ANY IDLERS OR ROLLERS IN THE CABLE ASSEMBLY
being inspected. IF YES, record whether the IDLERS and/or ROLLERS are WORKING
PROPERLY. Idlers and rollers should rotate freely and should not wobble as the cable passes
through them. If the idlers or rollers are not functioning properly, record if the CABLE is
being DAMAGED by the malfunction of the idlers or rollers.

Record whether the GATE OR VALVE CONNECTION IS OBSERVABLE. IF YES,
record the evidence of GATE OR VALVE CONNECTION MOVEMENT by estimating the
relative movement to the nearest 1/8 in. between the gate or valve and the end of the cable
(Fig. 34).

If the worst section of
cable or chain is located
counter-clockwise from
point A, the value will
be negative.

The gate or valve
should be in the closed
position to take the
measurement.

A

LOCATION (ft.) TO THE
CHAIN OR CABLE DISTRESS
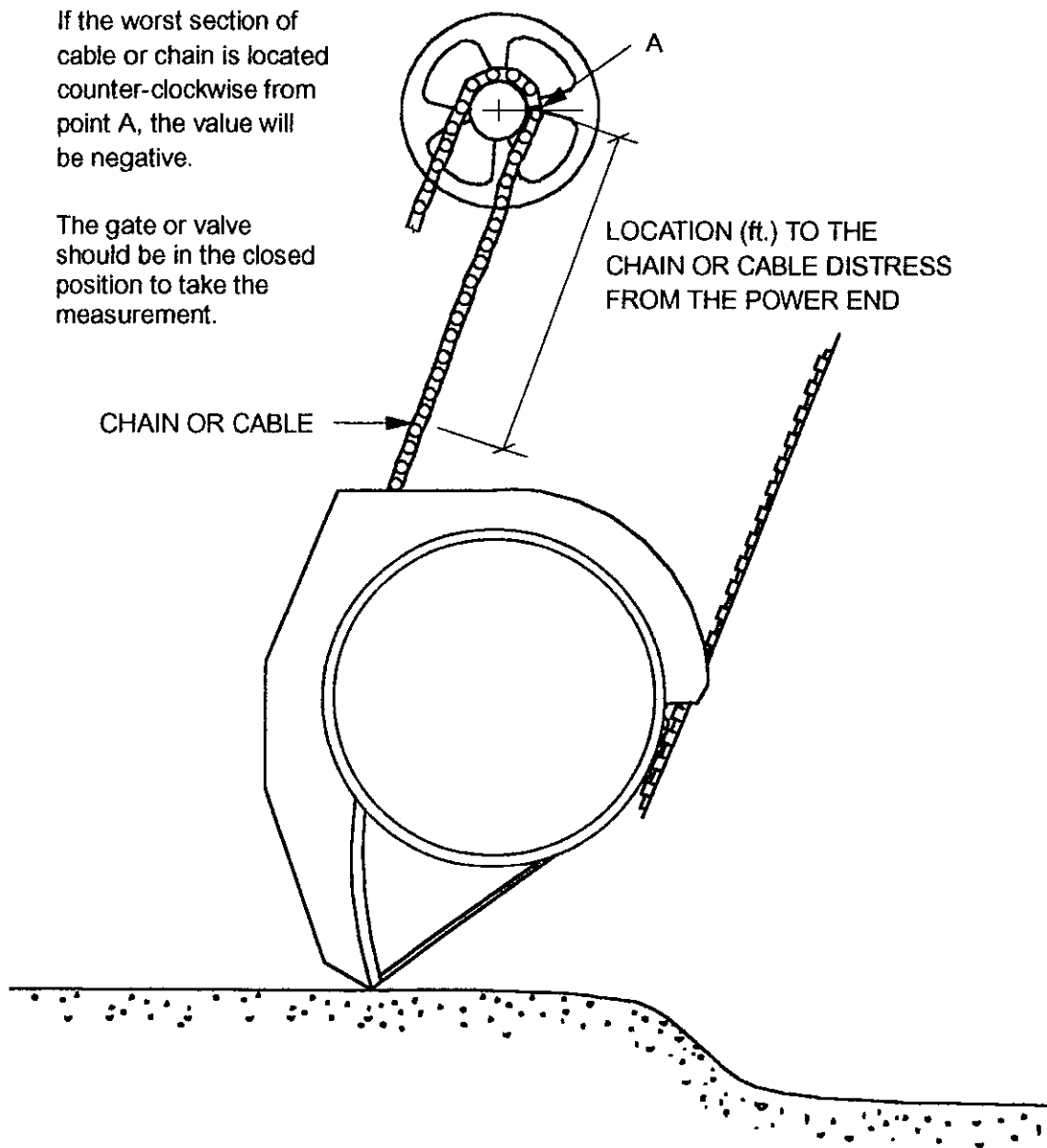FROM THE POWER END

CHAIN OR CABLE

Figure 49. Location Identification for Cable and Chain Distresses

Figure 50. Cable Bird Cage

Figure 51. Cable Protruding Core
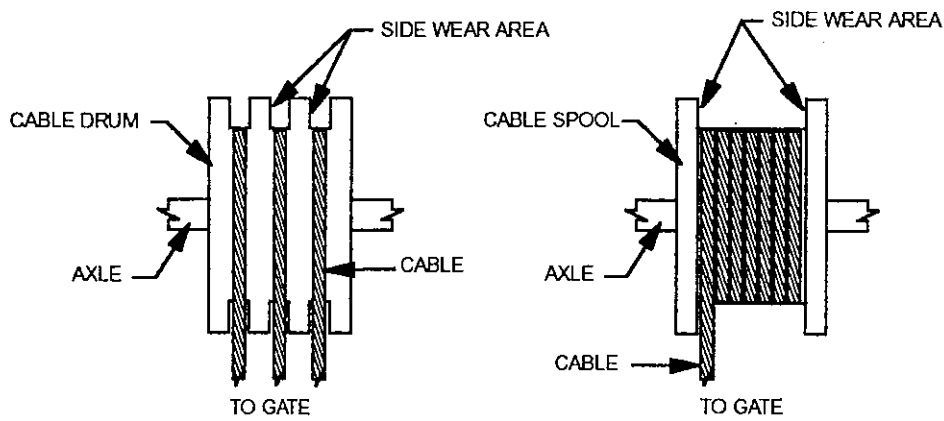
Figure 52. Drum Wear Distresses

Condition Index

The following section contains the rules for calculating the individual CIs for the cable assembly distresses. Distress descriptions and example illustrations are also provided.

Noise, Jumping, and Vibration

See noise, jumping, and vibration for the exposed gear assembly (Chapter 4)

Outer Wire Wear

Definitions and Causes: Wire wear is the reduction in diameter of the cable wires. Wear occurs when the cable moves over drums or through abrasive mediums.

Measurements and Limits: The percentage of wear on the outer wires, X, is recorded. The limiting value for this distress is

$$X_{MAX} = 33\% \tag{9.1}$$

[29]

Example: The outer wires of a cable were worn an average of 20%. The CI for the cable wear distress is

$$CI = 100(0.4)^{(20/33)} = 57$$

The CI is rated marginal.

Reduction In Rope Diameter

Definition and Causes: A reduction in the cable diameter may be attributed to excessive external abrasion, internal or external corrosion, loosening or tightening of rope lay, inner wire breakage, and/or rope stretch.

Measurement and limits: The new diameter of the cable, X_{NEW}, and the diameter at the minimum cross section, X_{WORN}, are recorded on the inspection form. The difference

between these diameters is

$$X = X_{NEW} - X_{WORN} \qquad\qquad (9.2)$$

The values for X_{MAX} are

Original Diameter of Cable	X_{MAX}
up to 3/4 "	3/64"
7/8" to 1-1/8"	1/16"
1-1/4" and up	3/32"

[29]

Example: The inspection of a cable assembly revealed significant reduction in diameter of the cable. The new and current diameters were

$$X_{NEW} = 1 \text{ in.}$$

$$X_{WORN} = 31/32 \text{ in.}$$

Equation 9.2 gives the difference between these diameters

$$X = 1 \text{ in.} - 31/32 \text{ in.} = 1/32 \text{ in.}$$

With the original diameter between 7/8 in. and 1-1/8 in., X_{MAX} is 1/16 in.. The CI is calculated with Equation 2.1

$$CI = [100(0.4)^{(1/32)/(1/16)}] = 63$$

This CI is rated fair.

Corrosion

Definition and Causes: Corrosion of cables can cause sudden failure with little warning. And as cables often corrode from the inside out, it is important to determine if any internal corrosion is occurring. Corrosion of cables is caused by interaction with the

environment and a lack of lubrication.

Measurement and Limits: If there is evidence of slight corrosion, such as slight discoloring, the CI will be 70. However, if there is pitting or severe rusting of the cable, the CI will be 40 [30].

Example: While inspecting the cable near the splash zone in a cable assembly, severe rusting was detected. The CI for corrosion is

$$CI = 40$$

The CI is rated marginal.

Bird Cages, Kinks, and Protruding Core

Definition and Causes: A bird cage is a local area of severely unraveled cable (Fig. 50). Bird cages form when slack develops in the cable and that slack is suddenly removed. Bird cages can also be formed when the cable is wrapped too tightly around drums. Kinks are permanent distortions caused by loops being drawn too tightly. A protruding core occurs when the center strand protrudes through the outer strands (Fig. 51).

Measurement and Limits: The existence of bird cages, kinks, and protruding cores is recorded in the inspection form. If any one or a combination of these three distresses occur the CI will be 40 [29].

Example: A kink was found in a cable assembly during an inspection. The CI for this distress is

$$CI = 40$$

The CI is rated marginal.

Unlayed Strands

Definition and Causes: A cable is made up of several individual strands that are uniformly distributed. Sometimes the strands become displaced along one side of the rope. These displacements can be caused by the rubbing around or against an object.

Measurement and Limits: The existence of any unlayed strands are recorded in the inspection form. If unlayed strands exist the CI will be 40.

Example: Several unlayed strands were found during a cable assembly inspection. The CI for the unlayed strands is

$$CI = 40$$

The rating for this CI is marginal.

Wire Breakage

Definition and Causes: This distress deals with the number of broken wires in a length of cable known as a rope lay. Broken wires can be caused by excessive loads, fatigue, and wear.

Measurement and Limits: The maximum number of broken wires, X, in all of the strands within any one rope lay are recorded for each cable set. The limiting value of broken wires per rope lay is

$$X_{MAX} = 6 \tag{9.3}$$

[29]

Example: Four broken wires were found in one rope lay of a cable. The CI for broken wires is

$$CI = [100(0.4)^{4/6}] = 54$$

The CI is rated marginal.

Unequal Tension

Definition and Causes: In order for a cable operated structure to be operating properly, the cables should have equal tension. For multiple cables, it is important that all the cables be tensioned uniformly. Some cables may be over-stressed if the load is not evenly distributed.

Measurement and Limits: The number of cables which are relatively untensioned, X, are recorded in the inspection form. The limiting value for untensioned cables is

$$X_{MAX} = 1 \tag{9.4}$$

Example: One cable had a different frequency when struck than the other cables in the set, signalling unequal tension. The CI for unequal tension is

$$CI = [100(0.4)^{1/1}] = 40$$

This CI is rated marginal.

Drum Wear

Definition and Causes: Drum wear is the reduction of steel in the cable drum through wearing. The cause for this wearing is the misalignment of the cable and drum during operation and wear due to normal use.

Measurement and Limits: The existence of drum wear or damage is recorded in the inspection form. If drum wear exists, an estimate of the groove wear is recorded. The groove wear is given in percentage of the cable diameter. If the estimated groove wear is less than 10% the CI is 70. If the estimated groove wear is equal to or greater than 10%, the wear is measured. The limiting value for groove wear is

$$X_{MAX} = 25\% \hspace{5cm} (9.5)$$

If side wear is evident, the CI must be less than or equal to 70.

[31]

Example: Drum wear was evident on a cable assembly. The estimated percentage of groove wear was 20%. The wear was then measured with a template and was found to be 15%. The CI for drum wear is

$$CI = [100(0.4)^{15/25}] = 58$$

This CI is rated fair.

Cable Drum Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Sheave Wear

See drum wear for the cable assembly (Chapter 9)

Sheave Bearing/Bushing Wear

See bearing/bushing wear for the exposed gear assembly (Chapter 4)

Sheave Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

Idlers/Rollers Wear

Definitions and Causes: The distress for idlers and rollers is the wear or wobbling of the idlers or rollers. As a groove is worn in the idler or roller, the rate of wear in the cable increases. Wobbling of the idler or roller can cause the cable to untrack. Wear and wobbling can be caused by normal use and improper lubrication. Wobbling can also be caused by wear between the idler or roller and the shaft on which it rotates.

Measurements and Limits: If the idlers or rollers do not work properly, but are not causing damage to the cable, the CI is 70. If damage is occuring to the cable because the idlers or rollers are not working properly, the CI is 40.

Example: A deep groove was cut in a idler, causing exstensive damage to the cable. The CI for idlers/rollers is

$$CI = 40$$

The CI is rated marginal.

Gate Or Valve Connection Movement

See strut connection movement for the strut arm assembly (Chapter 7)

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The two critical distresses in the cable assembly are the bird cage, kink, or protruding core distress and the wire breakage distress. The CIs from the remaining thirteen distresses will be used to calculate the weighted CI_w (Equation 2.5). The weighting factors for those thirteen distresses can be found in Table 19.

Field Test

The bar charts in Figures 53 and 54 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective condition index from the various field tests to the condition index calculated from the rules for two cable distresses. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts condition indexes are summarized below.
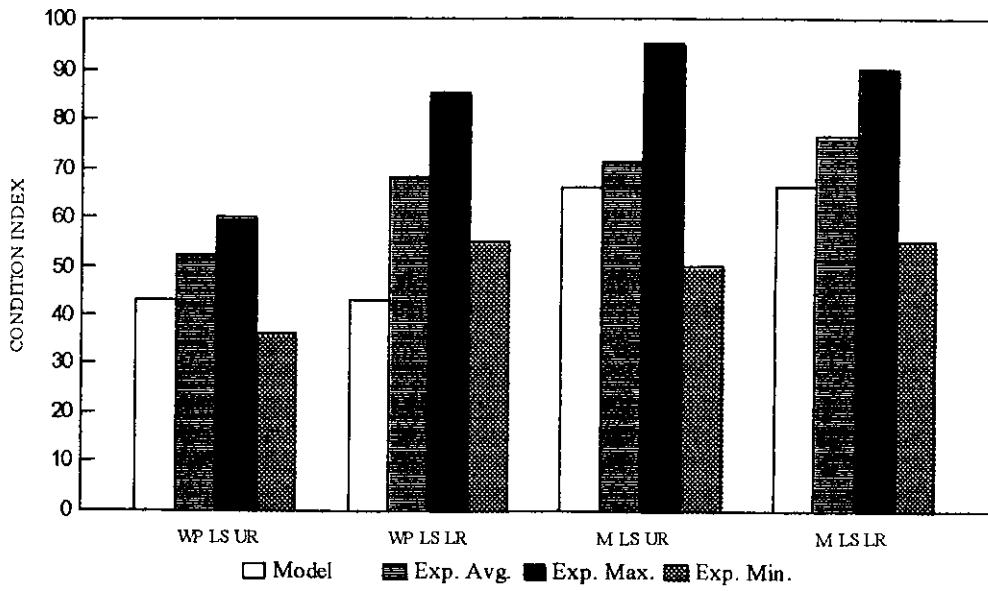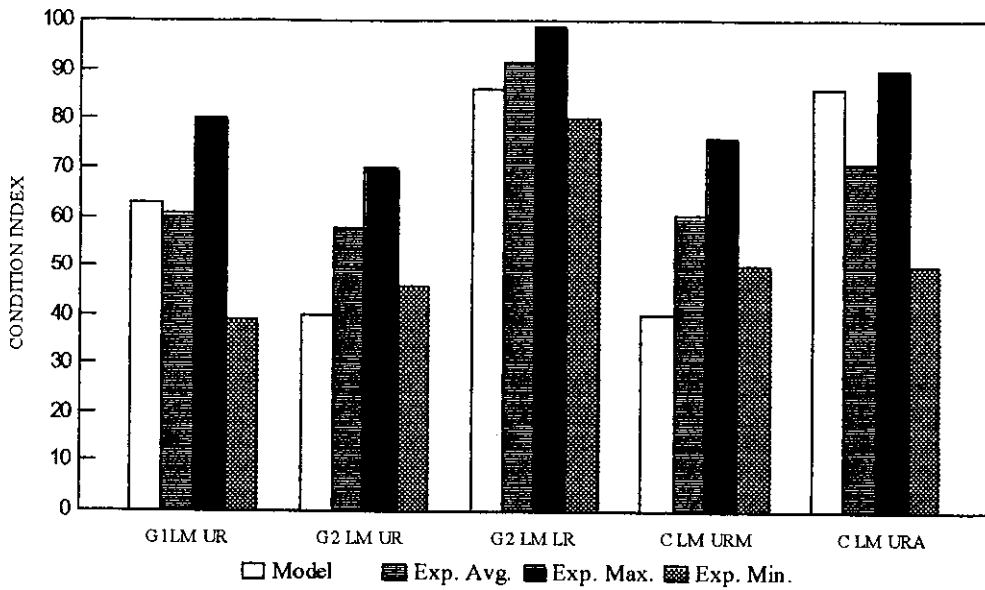
Figure 53. Outer Wire Wear: Cable Assembly

Figure 54. Wire Breakage: Cable Assembly

Noise, Jumping, Vibration

The noise, jumping, and vibration distress was not calibrated because noise, jump, or vibration was not observed in cables. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. This distress was not calibrated for the cable assembly. However, it was calibrated for the enclosed gear assembly.

Outer Wire Wear (Fig. 53):

The outer wire wear distress was observed in four of the twenty-two assemblies which were inspected during the field tests. For the remaining eighteen assemblies, the calculated CIs were 100 and the experts' average CIs were 90 or above. In the four assemblies for which wire wear was observed (Upper Right Sector Lock Gate W.P. Franklin, Lower Right Sector Lock Gate W.P. Franklin, Upper Right Sector Lock Gate Moorehaven, and Lower Right Sector Lock Gate Moorehaven), the assemblies were used to operate sector lock gates. In all four cases the experts' average CI was higher than the calculated CI, however, in three of those cases the experts' average CI was within 10 points of the calculated CI. Because the value of X_{MAX} was taken from the Safety and Health Requirement Manual [29] it will not be adjusted.

Reduction In Rope Diameter

The reduction in rope diameter was observed in three cable assemblies during the field tests. The measurement technique used to determine the amount of reduction, however, was inaccurate. A new technique is now described in the inspection form comments. While this distress cannot be calibrated, the value of X_{MAX} was taken from the Safety and Health Requirement Manual [29].

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Corrosion

The corrosion distress was not calibrated because corrosion was not observed in cables. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. While this distress cannot be calibrated, the rule for the corrosion of the cable assembly was based on the Safety and Health Requirement Manual [29].

Bird Cages, Kinks, and Protruding Core

The bird cages, kinks, and protruding core distress was not calibrated because the cable assemblies observed did not show this type of damage. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. Although this distress was not calibrated, the experts agree with the Wire Rope Users Manual [30] which states that wire rope should be replaced immediately if any one of these three types of damage exists in the cable. This corresponds well to the rules for this distress.

Unlayed Strands

The unlayed strands distress was not calibrated because no unlayed strands were observed in cables during the field tests. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above.

Wire Breakage (Fig. 54):

Broken wires were observed in five of the twenty-two cables assemblies inspected during the field trips. The calculated CIs were 100 and the experts' average CIs were 90 or above for all twenty-two assemblies for which wire breakage was not observed. For the five cable assemblies for which broken wires were observed, the calculated CIs were higher than the experts' average CIs for two cases and were lower on the remaining three cases. The rule in Section 9.3 for wire breakage was based on the Wire Rope Users Manual [30].

Unequal Tension

The equal tension distress was not calibrated because unequal tension was not observed in cables during the field tests. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above.

Drum Wear

The drum wear distress was not calibrated because drum wear was not observed in the cable drums during the field tests. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. Although the drum wear distress was not calibrated, the current rule is based on discussion with the experts.

Drum Anchorage Movement/Deterioration

The drum anchorage movement/deterioration distress was not calibrated because no movement or deterioration was detected in any of the drum anchorages. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. The anchorage movement/deterioration distress was calibrated for the exposed gear assemblies (Chapter 4).

Sheave Wear

The sheave wear distress was observed on two cable assemblies at the W.P. Franklin Lock. The sheave wear distress was not on the inspection form when the distress was observed and therefore cannot be calibrated. Although the sheave wear distress was not calibrated, the current rule is based on discussion with the experts.

Sheave Bearing/Bushing Wear

The sheave bearing/bushing wear distress was not calibrated because no wear was observed in the sheaves during the field tests. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. The bearing/bushing wear distress was calibrated for

the exposed gear assemblies (Chapter 4).

Sheave Anchorage Movement/Deterioration

The sheave anchorage movement/deterioration distress was not calibrated because no movement or deterioration was detected in any of the sheave anchorages. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above. The anchorage movement/deterioration distress was calibrated for the exposed gear assemblies (Chapter 4).

Idler/Roller Wear

The idler/roller wear distress was observed on two cable assemblies at the W.P. Franklin Lock. The idler/roller distress was added to the inspection form after the first field test but was not observed in succeeding field tests. Therefore, the distress cannot be calibrated. Although the idlers/rollers distress was not calibrated, the current rule is based on discussion with the experts.

Gate or Valve Connection Movement

The gate or valve connection distress was not calibrated because no relative movement was detected at the gate or valve connections. Hence, the calculated CIs were all 100 and the experts' average CIs were 90 or above.

Assembly CI (Fig.55):

The assembly CI for the cable assembly was calibrated for four assemblies. For two of the correlation between the model CIs and the experts' average CIs is poor (18 and 31 points apart), and for the other two calibrated assemblies the model CIs were within 4 points of the experts' average CIs. In only one case (Upper Right Sector Lock Gate Moorehaven) did the model CI and the experts' average CI fall into a different zone. In all four cases wire breakage, a critical distress, controlled the assembly CI.
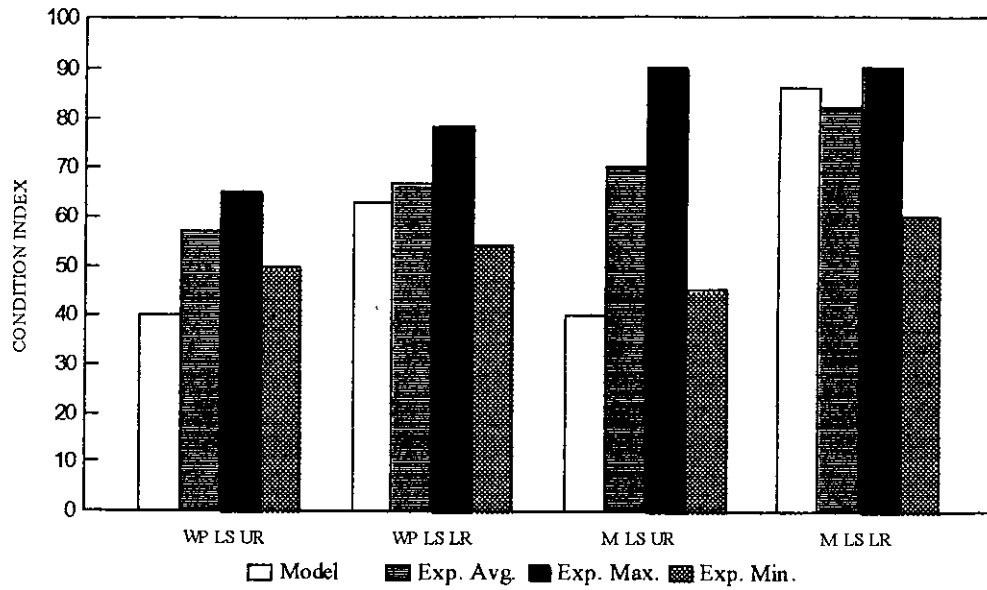
Figure 55. Cable Assembly CI

CHAPTER 10. CHAIN ASSEMBLY

Component Identification

Definitions and sketches for components of the chain assembly are presented in the following paragraphs.

Chain

A chain is a series of links connected to one another. Chain lifting systems are sometimes used to raise or lower dam or lock structures (Fig. 56). The chain gets lifted and wound over a sprocket type device during the operation of the assembly.

Roller Chain

A roller chain consists of roller bushings, side plates, and pins (Fig. 57). The roller bushings turn on the pins, thereby reducing the friction between the chain and the sprocket. The rollers fit in between the sprocket teeth.

Round Chain

The links of this chain are oval shaped and are permanently fit into one another (Fig. 57).

Sprocket

The sprocket is the component which retrieves the chain as it rotates. The chain fits in the sprocket teeth.

Inspection Form With Comments

The following pages (Fig. 58) present Parts 1 and 2 of the inspection forms for the chain assembly. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).
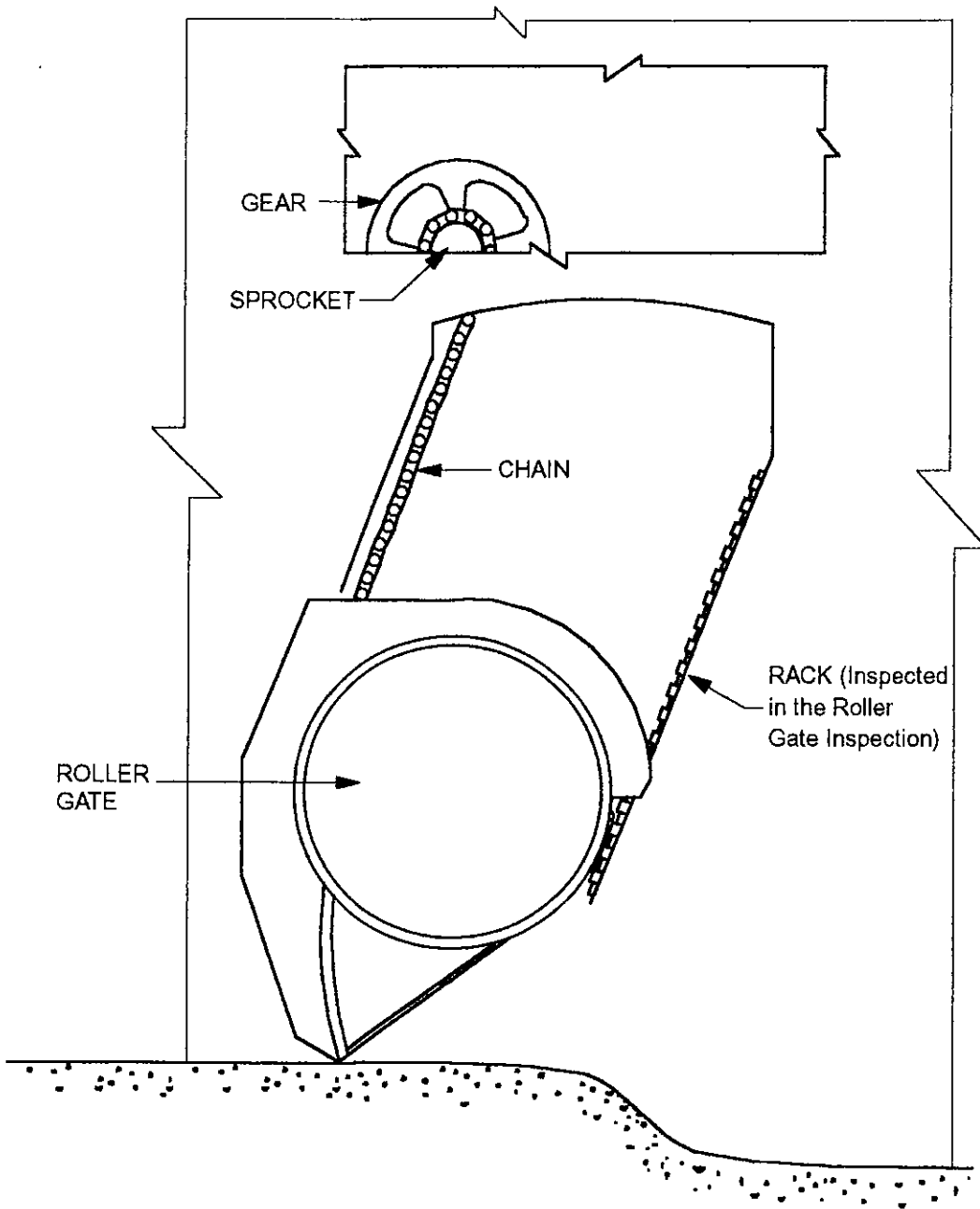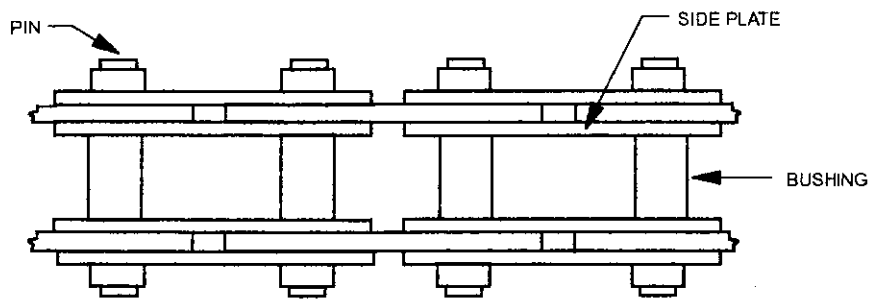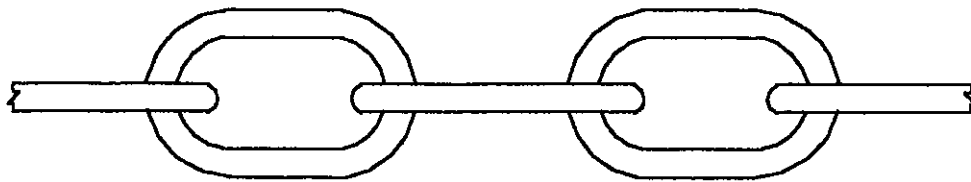
Figure 56. Side View of Roller Dam Gate Operating Equipment

ROLLER LINK

ROUND LINK

Figure 57. Chain Link Schematic

Part 1 Comments: Field data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which valve or dam gate is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Identify whether the chain is a ROLLER or ROUND LINK TYPE.

Observation of the chain assembly during gate or valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, and/or vibration is NORMAL.

LINKAGE WEAR/ELONGATION of the chain occurs between the links of the chain (Fig. 59). Record the LENGTH OF WORN/ELONGATED LINKS. This distance can be measured on a roller link chain by placing a tape measure along the chain and measuring from the center to center of several consecutive link pins (Fig. 59). For a round link, measure from end to end of the links (Fig. 59). To get a more accurate estimate of total wear and elongation, measure the wear in ten to twenty consecutive links and divide the measured distance by the number of links. The worst worn links will most likely be those which ride on the sprocket most frequently, if the gate operates at a relatively constant elevation. Also record the LENGTH OF NEW LINKS. This distance can be obtained from construction drawings. If construction drawings are not available, measure the distance between links which get little use, and use this distance as an estimate of the distance between new links.

Record the NUMBER OF CRACKS in the chain links. Also record the LOCATION of the cracked links from the power end (Fig. 49).

Many times after a structure has been in the same position for some time the links will lock together and not bend around the sprocket. Record a yes (Y) if the chain will not bend around the sprocket or, in other words, the chain LINKS are FROZEN. If links are frozen, they will often remain bent in the shape of the sprocket after they have been loaded. If there are frozen links, record whether they cause LIMITED OPERATION of the structure. The structure may have to be raised higher than normal to check the probable problem links. Also record the LOCATION of the frozen links from the power end (Fig. 49).

The presence of excessive CORROSION on the chain is a potential problem. Record YES if there is SIGNIFICANT CORROSION (more than general scaling). If yes, indicate if there is SEVERE PITTING (1/8 inch pits or greater) in a dense pattern or GENERAL THICKNESS REDUCTION of 10% or greater in local areas. Also record the LOCATION of the corrosion from the power end (Fig. 49).

Part 2 Comments: Field data

SPROCKET WEAR is wear due to the chain constantly rubbing over the sprocket teeth. Record if there is WEAR of the sprocket teeth. IF YES, ESTIMATE the % of REDUCTION OF the SPROCKET TOOTH. If the estimated reduction is GREATER THAN 10%, MEASURE the % of REDUCTION OF the SPROCKET TOOTH. One way to measure the % of reduction is to measure the width of a sprocket tooth which sees little contact and assume that width as the new sprocket tooth width and compare that width to the measured width of a worn tooth. The new tooth width can also be obtained from construction drawings.

Record any evidence of MOVEMENT greater than 0.002 at the SPROCKET ANCHORAGE as the gate is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement. Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment. Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE nuts at this connection if the BOLTS are EXPOSED.

Record if the GATE OR VALVE CONNECTION IS OBSERVABLE. IF YES, record the MOVEMENT at the END CONNECTION by visually observing any movement as the chain goes from slack to full tension and estimating the movement to the nearest eighth of an inch (Fig. 34). To further enhance the visual observation, one can place a dial gauge at this location.
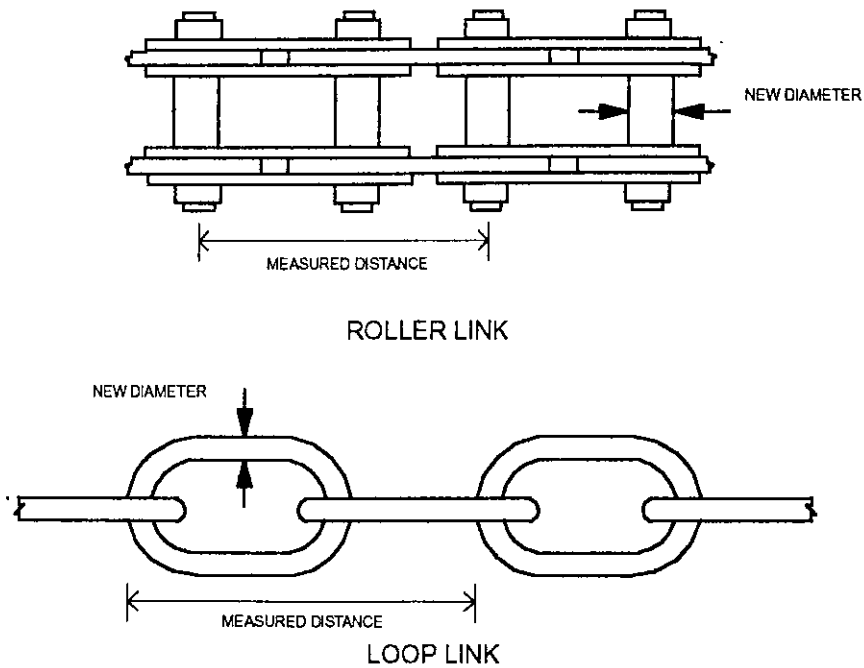
Figure 59. Chain Linkage Wear

Condition Index Rules

The following section contains the rules for calculating the individual CIs for the chain

assembly distresses. Distress descriptions and example illustrations are also provided.

Noise, Jumping, and Vibration

See noise, jumping, and vibration for the exposed gear assembly (Chapter 4)

Linkage Wear/Elongation

Definition and Cause: Linkage wear/elongation can be caused by the reduction of

cross-sectional area of chain links at the point of contact, wear of the connecting pins and

rollers, and elongation of the chain links. For roller links the wear occurs between the pin and

the side plate and for round links the wear occurs where the links interconnect (Fig. 59).

Linkage wear and elongation are caused by normal operation of the chain assembly, through the interaction between the chain links, misalignment of the sprocket, or excessive loading.

Measurement and Limits: The evaluation of the chain link wear/elongation distress will be accomplished by comparing the length of a new link to the current chain link length. The difference, X_1, between the length of the new links, X_{NEW}, and the measured length, X_{WORN}, is

$$X_1 = X_{WORN} - X_{NEW} \qquad (10.1)$$

The percentage of wear, X, is

$$X = (X_1 / X_{NEW})(100) \qquad (10.2)$$

The limiting value for linkage wear/elongation is

$$X_{MAX} = 10\ \% \qquad (10.3)$$

[29]

Example: In the inspection of a chain assembly the measured distance between pins of a roller link was

$$X_{WORN} = 14.50\ \text{in.}$$

The new distance between pins was

$$X_{NEW} = 14.00\ \text{in.}$$

Applying Equation 10.1 gives

$$X_1 = (14.50 - 14.00) = 0.50\ \text{in.}$$

The percentage of wear/elongation in the chain is

$$X = (0.50 / 14.00)(100) = 3.5\%$$

The CI for linkage wear/elongation is

$$CI = [100(0.4)^{3.5/10}] = 73$$

The CI is rated good.

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Frozen Links

Definition and Causes: The links of a chain are frozen when they will not bend properly around the sprocket or remain bent when loaded. Links may become frozen when the gate is not moved frequently. Frozen links are caused by inadequate lubrication, interaction with the environment (corrosion), excessive overloads, material buildup in chain joint, peening of side plate edges, and misalignment [32].

Measurement and Limits: If the chain links in a chain set are frozen it is recorded in the inspection form. The CI will be 70 if there are frozen links but the equipment is still operational. However, if the structure operation is limited due to the frozen links, the CI will be 40.

Example: A chain assembly which was not operated often had several frozen links. The operation of the structure was not limited by the frozen links, therefore, the CI for the frozen links distress is

$$CI = 70$$

The CI is rated good.

Corrosion/Pitting

See corrosion for the strut arm assembly (Chapter 7).

Sprocket Wear

Definition and Causes: Sprocket wear is the wear of the sprocket teeth. This wear occurs because of the interaction between the sprocket teeth and the chain links. Normal use, lack of lubrication, and misalignment [32,33] can cause sprocket wear.

Measurement and Limits: Measurement of sprocket wear will be made by estimating the percentage of reduction of original sprocket tooth, X. If the estimated value of reduction is greater than 10%, a measured percentage of reduction, X, is found. The limiting value for sprocket wear will be

$$X_{MAX} = 20 \text{ \%} \tag{10.5}$$

Example: The estimated percentage of reduction for a worn sprocket tooth was

$$X = 5 \text{ \%}$$

The CI for sprocket wear is

$$CI = 100(0.4)^{5/20} = 80$$

From Table 1, the CI for sprocket wear is described as good.

Sprocket Anchorage Movement/Deterioration

See anchorage movement/deterioration for the exposed gear assembly (Chapter 4)

End Connection Movement

See end connection movement for the strut arm assembly (Chapter 7).

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The lone critical distress in the chain assembly is the cracks distress. The CIs from the remaining eight distresses will be used to calculate the weighted CI_w (Equation

2.5). The weighting factors for those eight distresses can be found in Table 20.

Field Test

The chain assembly was not observed during the first two field tests in the Jacksonville and Louisville Districts, therefore, data to calibrate the rules for the chain assembly could not be obtained. On the third field trip the chain assembly was observed and discussion with the experts was helpful in revising the inspection form and rules for the chain assembly. The rules for similar distresses in other assemblies were used as guidelines for the chain assembly rules.

Noise, Jumping, Vibration

The noise, jumping, and vibration distress could not be calibrated for the chain assembly. However, the distress was calibrated and the calculated CI closely approximated the experts' CI for the enclosed reduction gear assembly.

Linkage Wear/Elongation

The linkage wear/elongation distress could not be calibrated but was tested during the third field test. The technique described in Section 10.2 seemed to work reasonably well. The value of X_{MAX} was obtained from the <u>Safety and Health Requirements Manual</u>.

Cracks

Although the cracks distress could not be calibrated, the experts feel that cracks in a chain assembly are critical and should be repaired. The rule for the cracks distress corresponds well with the collective expert opinion.

Frozen Links

Although the frozen links distress could not be calibrated, the experts feel that frozen links in a chain assembly are serious and should be repaired. The rules for the frozen links

distress correspond well with the collective expert opinion.

Corrosion/Pitting

The corrosion/pitting distress could not be calibrated for the chain assembly. The rule for the corrosion distress was, however, calibrated for the strut arm assembly and the calculated CIs closely approximated the experts' averages.

Sprocket Wear

Although the sprocket wear distress could not be calibrated, the inspection questions and rules were written to closely resemble the questions and rules for cable drum wear which are presented in Chapter 9.

Sprocket Anchorage Movement/Deterioration

Although the sprocket anchorage movement/deterioration distress could not be calibrated, the anchorage movement/deterioration distress was calibrated for the exposed gear assembly (Chapter 4) and the enclosed gear assembly (Chapter 5).

End Connection Movement

Although the gate connection movement distress could not be calibrated for the chain assembly, the distress was calibrated for the strut arm assembly. The calculated CIs closely approximated the experts' average CIs.

Assembly CI

Although the combined CI could not be calibrated for the chain assembly, the weighting factors used to calculate the assembly CI (Table 20) were obtained from the experts.

CHAPTER 11. HYDRAULIC CYLINDER ASSEMBLY

Component Identification

Definitions and sketches for components of hydraulic cylinder are presented in the following paragraphs.

Hydraulic Cylinder

Hydraulic cylinders produce the force required to move the gate structure or lift and lower the valve structure.   Hydraulic cylinders are often used horizontally in gate structures (Fig. 6, 45).   Hydraulic cylinders are also used horizontally in conjunction with the rocker assembly in valve structures (Fig. 8) .   In some cases the hydraulic cylinders are used vertically directly above a vertical lift valve, i.e., therefore, a rocker arm is not needed.

Packing Plate

The function of the packing plate is to allow the piston rod to pass through the cylinder end without leakage of hydraulic fluid. The packing plate is located at the end of the hydraulic cylinder (Fig. 8).

Piston Rod

The piston rod extends from the hydraulic cylinder and transfers the force from the hydraulic cylinder to the strut (Fig. 8).

End Connection

The end connection is located at the end of the piston rod. Its function is to transfer force from the piston rod to the strut, rack, or rocker (Fig. 8).

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Part 1 Comments: Field data

Enter the PROJECT NAME on which the inspection will be performed, the DATE of the inspection, and for the GATE IDENTIFICATION, identify whether this is a lock gate, valve, or dam gate. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the hydraulic cylinder assembly during gate or valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION during operation and then indicate whether this noise, jumping, and/or vibration is NORMAL.

Record any evidence of MOVEMENT greater than 0.002 at the ANCHORAGE as the gate or valve is opened and closed. Evidence of movement can be observed visually or enhanced by placing a dial gage to monitor any movement (Fig. 61). Excessive concrete spalling may indicate a displacement occurred at this location at some time. Also, record the presence of any CORROSION (10% volume loss) of the steel portion or any CRACKED CONCRETE at the interface of the embedment. Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored. Indicate if there are any CORRODED (10% volume loss), MISSING OR BROKEN, or LOOSE nuts at this connection if the BOLTS are EXPOSED.

Record any relative MOVEMENT in the END CONNECTION between the rod and the attached component such as the rocker arm (Fig. 34), strut, cross head, etc., by visually observing any movement parallel to the cylinder and estimating the movement to the nearest eighth of an inch. To further enhance the visual observation, one can place a dial gage at this location.

Record evidence of any SURFACE CORROSION on the cylinder rod. If corrosion is present, check to see if PITTING of the rod has occurred. If so, record the number of pits in the worst foot along the length of the rod. Also record the LOCATION of the surface corrosion from the connection end.

Wipe the rod clean and observe and record the PERCENTAGE of surface area of the cylinder ROD which is SCORED greater than 1/64". Scoring is grooving along the length of the cylinder rod. Also record the LOCATION of the scoring from the connection end. If applicable, record the PEELING of CHROME from the surface of the rod. Also indicate whether any other SIGNIFICANT DAMAGE to the rod (such as nicks, bowing or the rod, etc.) has occurred.

Record any EVIDENCE OF RECENT OIL LEAKAGE. Record the NUMBER OF OIL DROPS that leak from the packing seal interface during one full STROKE (Fig. 61). Many times this can be accomplished by placing a sheet of paper below the cylinder end.

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Part 1 Comments: Field data (continued)

Record the amount of DRIFT or movement of the hydraulic rod. When the hydraulic cylinder is used for valve or dam gate operation, the valve or dam gate should be in the open position. When the hydraulic cylinder is used to operate a lock gate, the lock gate should be in the open position. Isolate the cylinder by closing all oil valves and measuring the drift in a fifteen minute interval with a ruler or a dial gage (Fig. 61).

Figure 60. (continued)

Part 2 Comments: Field data

Record if ANY GUIDES ARE USED IN THE HYDRAULIC CYLINDER ASSEMBLY. IF
YES, record if the GUIDES SLIDE SMOOTHLY. Also record if the GUIDES ARE
DAMAGED. If the guides are damaged, record if THE HYDRAULIC CYLINDER is
BEING DAMAGED.
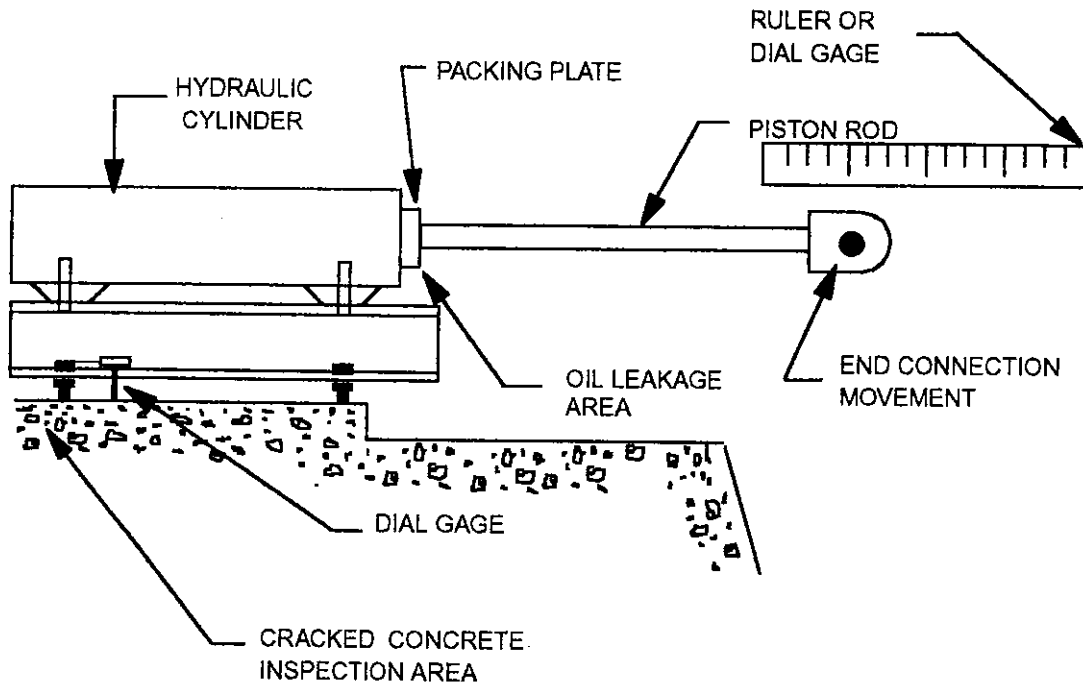
Figure 61. Hydraulic Cylinder Assembly Distress Measurements

Surface Corrosion/Pitting of Rod

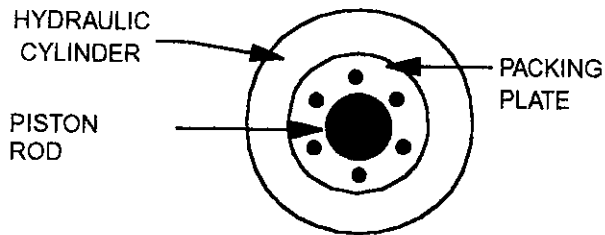**Definition and Cause:** Surface corrosion involves the scaling of steel material on the surface of the cylinder rod due to interaction with the environment. If this interaction continues pitting will occur, which is minor loss of steel in localized areas. Surface corrosion and/or pitting on the cylinder rod can be detrimental to the end seals in the hydraulic cylinder.

Measurements and Limits: Because any amount of corrosion on a cylinder rod can cause damage to the hydraulic cylinder seals, the CI will be 85 for any evidence of corrosion, including surface corrosion. For the condition of pitting, X is counted to be the number of pits per worst foot of rod. The limiting number of pits is

$$X_{MAX} = 30 \ pits \tag{11.1}$$

The CI for a rod with any amount of pitting can never be greater than 70.

Example: Ten pits were found on a cylinder rod during an inspection. The CI based on the number of pits is

$$CI = [100(0.4)^{10/30}] = 74$$

However, the CI can not be greater than 70 if any pits are found, therefore,

$$CI = 70$$

The CI is rated good.

Damaged Rod

Definition and Cause: Scoring of the rod refers to grooving which occurs in the cylinder rod. During normal use, a cylinder rod will wear in a uniform pattern of grooves. The causes for scoring include inadequate lubrication and normal wear during the opening and closing motion. The hydraulic rod is sometimes surfaced with chrome to protect the rod from

interaction with the environment. With normal use and exposure to the surrounding environment, the chrome sometimes peels off. Other damage such as nicking of the rod surface or bending of the rod is also possible. This damage could result from misuse of the equipment.

Measurement and Limits: The percentage of surface area of the rod which has scoring greater than 1/64 in., X, and the location of these grooves are recorded on the inspection form. Only the percentage of scoring is used in determining the condition of the rod. The limiting value for percentage of scoring is

$$X_{MAX} = 100\% \tag{11.2}$$

If there is evidence of chrome peeling off, the CI will be reduced by a factor of 0.70. If there is other significant damage to the rod such as chips or nicks, the CI will be reduced by a factor of 0.55.

Example: Scoring greater than 1/64 in. was found on 50% of a cylinder rod during an inspection of a hydraulic cylinder assembly. Some of the chrome surface on the rod was peeling off. For the scoring distress

$$X = 50\%$$

Using Equation (2.1) and the value of X_{MAX} from Equation (11.2), the CI for scoring is

$$CI = [100(0.4)^{50/100}] = 63$$

The CI is reduced because of peeling of the chrome. The CI for damage of the rod is

$$CI = (63)(0.70) = 44$$

The CI is rated marginal.

Oil Drippage

Definition and Cause: Oil drippage can occur at or near the packing plate in the hydraulic cylinder. Excessive cylinder pressure, damage to the rod, or wear of the packing plate from normal use can be the cause of oil drippage.

Measurement and Limits: The number of oil drops, X, that leak from the packing seal interface are recorded in the inspection form. The limiting value for the number of drops during a full stroke is

$$X_{MAX} = 20 \text{ drops} \tag{11.3}$$

If there is evidence of recent leakage, the CI can be no larger than 85.

Example: Twelve drops of oil leaked from the packing plate of a hydraulic cylinder. The CI for oil drippage is

$$CI = [100(0.4)^{12/20}] = 58$$

The CI is rated marginal.

Drift

Definition and Cause: When a structure utilizes a hydraulic cylinder and all oil valves are closed, one expects little movement of the supported load. Drift distress is the movement of the hydraulic rod with maximum load on the rod. For valve structures with horizontal cylinders, the load is the dead load of the structure when suspended. For sector gear and rack systems, there is normally no dead load due to the structure but conditions due to water flow, wind, etc. may create a load condition at the time of the inspection. On a sector gate, the load may be caused by water head differential or water flow as the gate is opened.

Measurement and Limits: The total amount of drift, X, is the movement recorded in a 15 minute interval. The limiting value for drift for a valve structure (loaded) is

$$X_{MAX} = 1 \text{ in.} \tag{11.4}$$

The limiting value for a lock gate structure (non-loaded) is

$$X_{MAX} = 1/4 \text{ in.} \tag{11.5}$$

The limiting value for a dam gate structure (loaded) is

$$X_{MAX} = 1/16 \text{ in.} \tag{11.6}$$

Example: The amount of drift found in a hydraulic cylinder used for valve operation was

$$X = 1.25 \text{ in.}$$

The CI for drift in this hydraulic cylinder is

$$CI = [100(0.4)^{1.25/1}] = 32$$

From Table 2, the CI for drift is rated poor.

Damaged Guides

Definitions and Causes: Cylinder guides can become corroded over time. Guide anchorages can also deteriorate or become loose. When this occurs, the guide assembly no longer moves smoothly as the hydraulic cylinder is operated. Corrosion and deterioration of the guides can be caused by interaction with the environment.

Measurement and Limits: If the guide does not slide smoothly as the hydraulic cylinder is operated, it is recorded in the inspection form. The CI will be 70 if the guide does not slide smoothly. If there is damage to the guides , the damage is also recorded in the inspection form. The CI will be 40 if damage can occur to the hydraulic cylinder because of the damaged guides.

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Example: The guide of a hydraulic cylinder jerked as the assembly was being operated. The CI for guides is

$$CI = 70$$

The CI is rated excellent.

Assembly CI

The assembly CI will be calculated with Equations 2.5, and 2.6 (See Chapter 2: Assembly Distress). The experts did not consider any of the distresses for the hydraulic cylinder critical, therefore, Equation 2.5 will be used to calculate the assembly CI. The weighting factors for the hydraulic cylinder distresses can be found in Table 21.

Field Test

The bar charts in Figures 62 to 65 (see Tables 23 through 25 for the abbreviation definitions) compare the experts' subjective condition index from the field tests to the condition index calculated from the rules for four hydraulic cylinder distresses. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts condition indexes are summarized below.

Noise, Jumping, Vibration

The noise, jumping, and vibration distress was not calibrated because no noise, jump, or vibration in hydraulic cylinders was observed. Hence, the calculated CIs were all 100 and the expert's averaged condition indexes were 90 or above. The noise, jumping, and vibration distress was calibrated in the enclosed gear assembly.

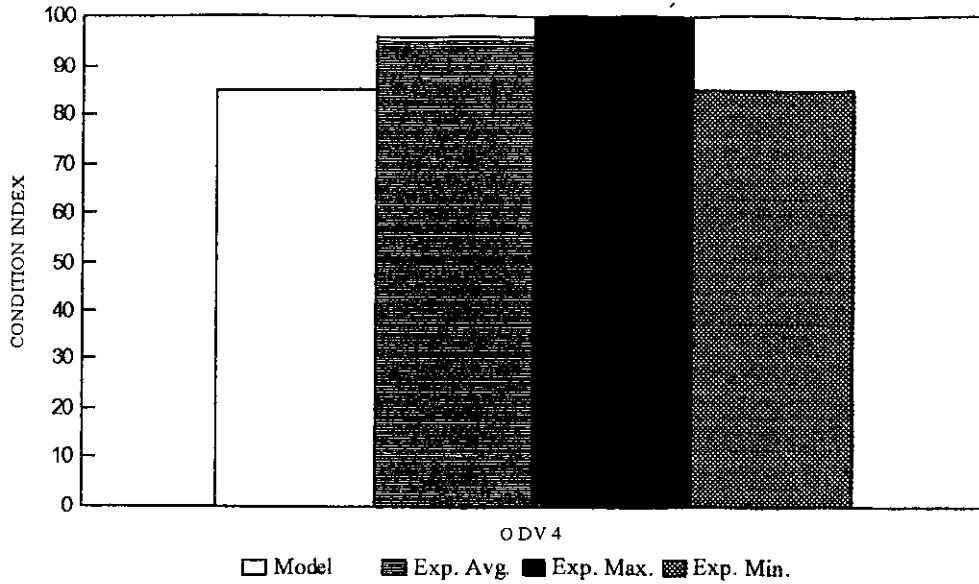**Figure 62. Anchorage Movement/Deterioration: Hydraulic Cylinder Assembly**
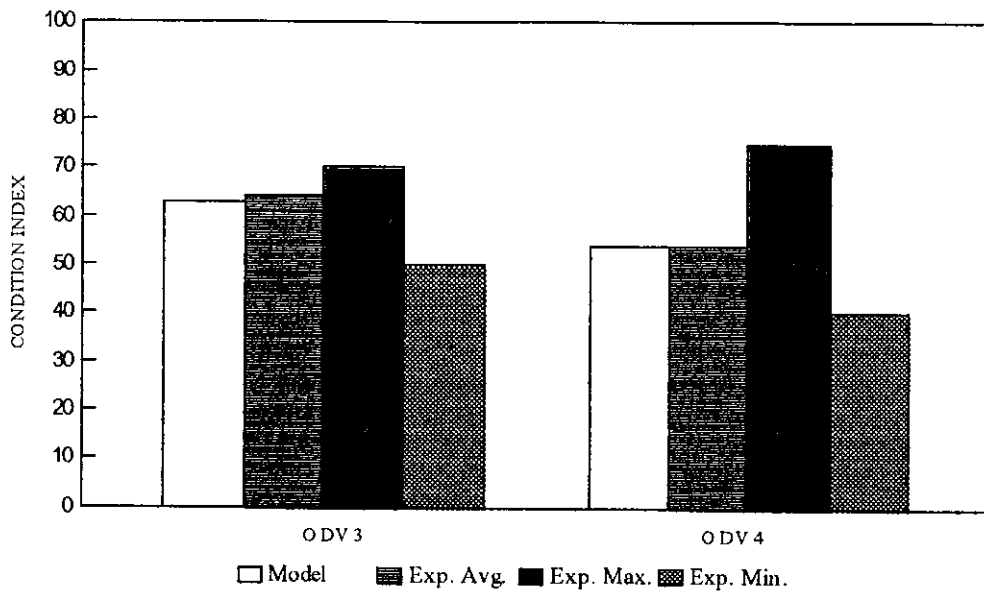

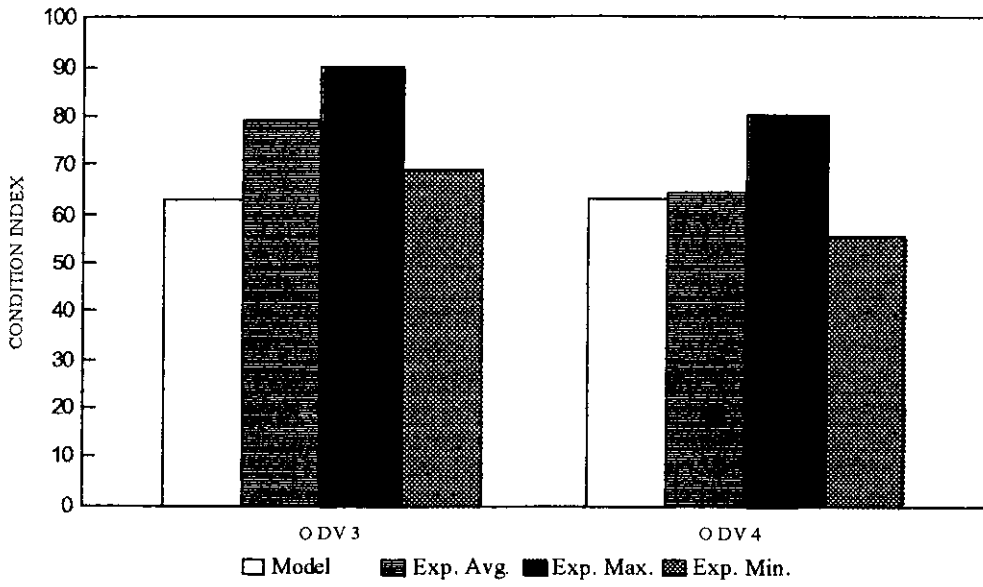**Figure 63. Corrosion/Pitting of Rod: Hydraulic Cylinder Assembly**

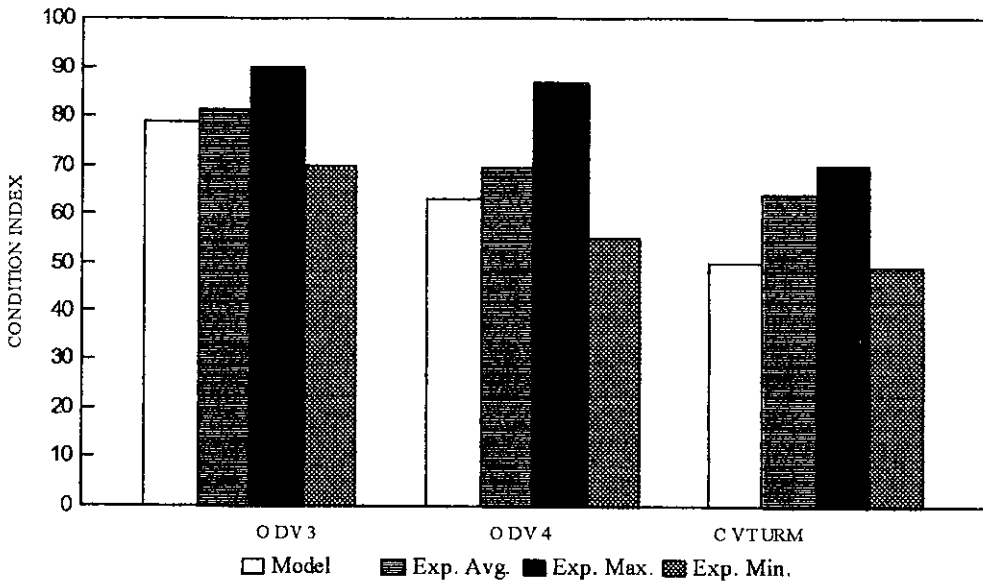**Figure 64. Oil Leakage: Hydraulic Cylinder Assembly**

Figure 65. Drift: Hydraulic Cylinder Assembly

Anchorage Movement/Deterioration (Fig. 62):

In only one case (Ortona Vertical Lift Gate #4) was any anchorage deterioration observed (corrosion of nuts). The calculated value was 85. For the other hydraulic cylinder assemblies, no deterioration was recorded by the experts and the calculated CI is 100.

End Connection Movement

The end connection movement distress was not calibrated because no movement between the rod and rocker arm or cross heads in hydraulic cylinders was observed. Hence, the calculated CIs were all 100 and the expert's averaged condition indexes were 90 or above. The end connection movement distress was calibrated in the strut arm assembly.

Corrosion/Pitting of Rod (Fig. 63):

At the two locations where the corrosion/pitting of rod distress was observed (Vertical Lift Dam Gate #3 Ortona and Vertical Lift Dam Gate #4 Ortona) the calculated CI was less than 5 points from the expert average CI for each case.

Damaged Rod

The damaged rod distress was not calibrated because no damage was observed in the hydraulic cylinders. Hence, the calculated CIs were all 100 and the expert's averaged condition indexes were 90 or above.

Oil Leakage (Fig. 64):

The oil leakage distress was evident on two hydraulic cylinders during the field calibration. On one of these cylinders the experts average was closely approximated by the calculated CI with the difference being only 1 point (Ortona Lift Gate #4). On a similar cylinder, for which the same number of oil drops per cycle was observed (Ortona Lift Gate

#3), the calculated CI was the same. The experts' average, however, was 16 points higher.

Drift (Fig. 65):

The calculated CIs for the drift distress were within 5 points of the expert average CIs with the exception of one hydraulic cylinder (Filling Valve Cannelton) for which the difference was 17 points.

Assembly CI (Fig. 66):

The assembly CI for the hydraulic cylinder assembly was calibrated for three assemblies. The model CIs were within 4 points of the experts' average CIs for all three calibrated assemblies.
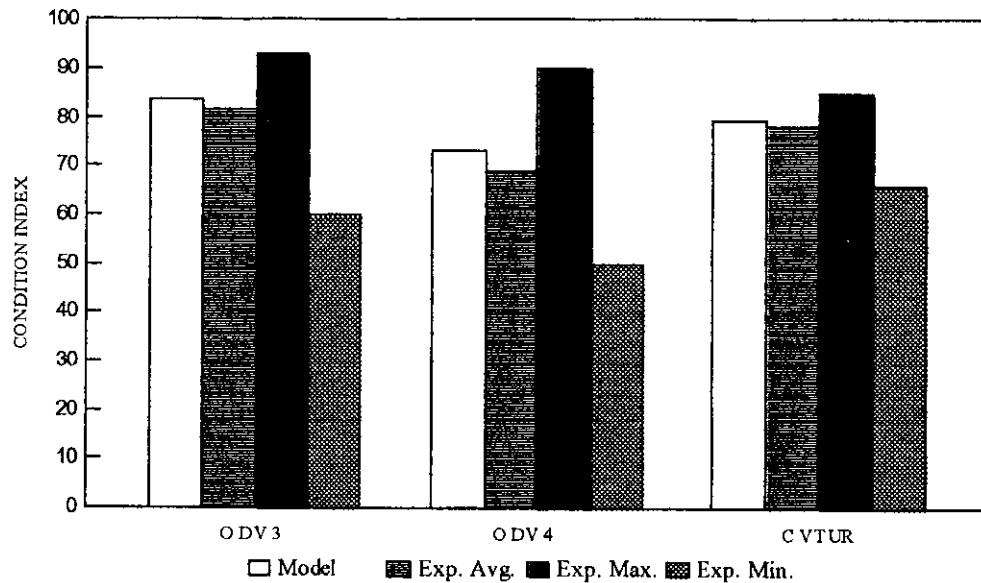

Figure 66. Hydraulic Cylinder Assembly CI

CHAPTER 12. COUPLING ASSEMBLY

Component Identification

Definitions and sketches for components of the coupling assembly are presented in the following paragraphs.

Coupling

A coupling is a joint between input and output shafts which generally contains meshing teeth to transfer force from one shaft to another (Fig. 10). The meshing teeth are enclosed in a hub.

Shaft

The shaft transfers force from one set of gears to another set of gears or to other equipment such as a cable drum (Fig. 10). The input shaft is the shaft on the power end.

Hub

The hub is the casing which contains the meshing teeth of the coupling.

Keyway

The keyway enables the transmission of torque from a shaft to the shaft-supported element.

Inspection Form With Comments

The following page (Fig. 67) presents the inspection form page for the coupling assembly which contains the field inspection questions. The side-by-side arrangement of the opposing pages displays specific explanations (right side) adjacent to the entry on the inspection form (left side).

Comments: Field Data

Enter the PROJECT NAME for this inspection, the DATE of the inspection, and, for the GATE IDENTIFICATION, identify which gate or valve is being inspected. Also enter the power transfer number (P.T.#) which can be found on Page 1 of the inspection form.

Observation of the coupling during gate or valve movement is a good indicator of problems. Record any indication of NOISE, sudden JUMPING, and/or VIBRATION and then indicate whether this noise, jumping, and/or vibration is NORMAL.

The presence of CRACKS on the coupling is usually not tolerated. Record the NUMBER OF CRACKS found on these components by visual observation.

The presence of excessive CORROSION on the coupling is a potential problem. Record YES if there is SIGNIFICANT CORROSION (more than general scaling). If yes, indicate if there is SEVERE PITTING (1/8 inch pits or greater) in a dense pattern or GENERAL THICKNESS REDUCTION of 10% or greater in local areas. Carefully observe the keyways(if there are any) for corrosion.

A FLEXIBLE COUPLING is an internal gear (Fig. 68). A small amount of lateral movement of the coupling may occur in a flexible type coupling [22]. A RIGID COUPLING is one for which no movement should occur, either in the lateral direction or with respect to the shaft. Rigid couplings are often bolted together.

Observe the shaft and hub when the operating equipment starts and stops. Record if there is any RELATIVE MOVEMENT BETWEEN THE INPUT SHAFT AND the HUB. Also record any RELATIVE MOVEMENT BETWEEN THE OUTPUT SHAFT AND the HUB. If either distress is marked yes, record if THE MOVEMENT IS EXCESSIVE. If the key in the keyway is loose or there is obvious long-term movement, the movement is excessive.

RELATIVE MOVEMENT
BOLTS
SHAFT

RIGID COUPLING

RELATIVE MOVEMENT
SHAFT

FLEXIBLE COUPLING
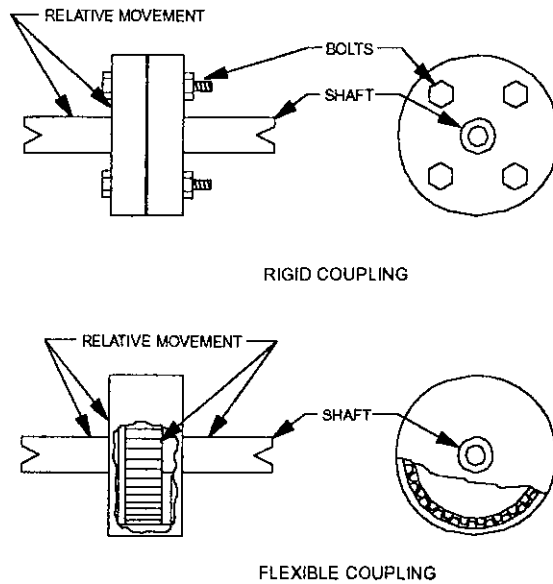
Figure 68. Coupling Relative Movement Measurement

Condition Index

The following section contains the rules for calculating the individual CIs for the coupling assembly distresses. Distress descriptions and example illustrations are also provided.

Noise, Jumping, and Vibration

See noise, jumping, and vibration for the exposed gear assembly (Chapter 4)

Cracks

See cracks for the exposed gear assembly (Chapter 4)

Corrosion

See corrosion for the strut arm assembly (Chapter 4)

Input Shaft and Hub Movement

Definitions and Causes: As the coupling becomes worn, relative movement between the input shaft and the hub begins to take place. As this wear becomes worse, the potential for failure becomes greater. Relative movement can be caused by normal use, inadequate lubrication, or corrosion.

Measurements and Limits: If relative movement between the input shaft and hub are observed, it is recorded in the inspection form. If relative movement is observed, the CI will be 70. If the movement is excessive the CI will be 40.

Example: Relative movement between the input shaft and hub was observed on a coupling assembly. The CI for the relative movement between input shaft and hub is

$$CI = 70$$

The CI is rated good.

Output Shaft and Hub Movement

See relative movement between output shaft and hub for the coupling assembly (Chapter 12).

Assembly CI

The assembly CI will be calculated with Equations 2.2, 2.5, and 2.6 (See Chapter 2: Assembly Distress). The three critical distresses in the coupling assembly are the cracks distress, the relative movement between the input shaft and hub distress, and the relative movement between the output shaft and the hub distress. The CIs from the remaining two distresses will be used to calculate the weighted CI_w (Equation 2.5). The weighting factors for those two distresses are in Table 22.

Field Test

The bar chart in Figure 69 (see Tables 23 through 25 for the abbreviation definitions) compares the experts' subjective condition index from the field tests to the condition index calculated from the rules for one coupling distress. Only data from assemblies with observed distresses are plotted. Comparisons between the calculated and experts condition indexes are summarized below.
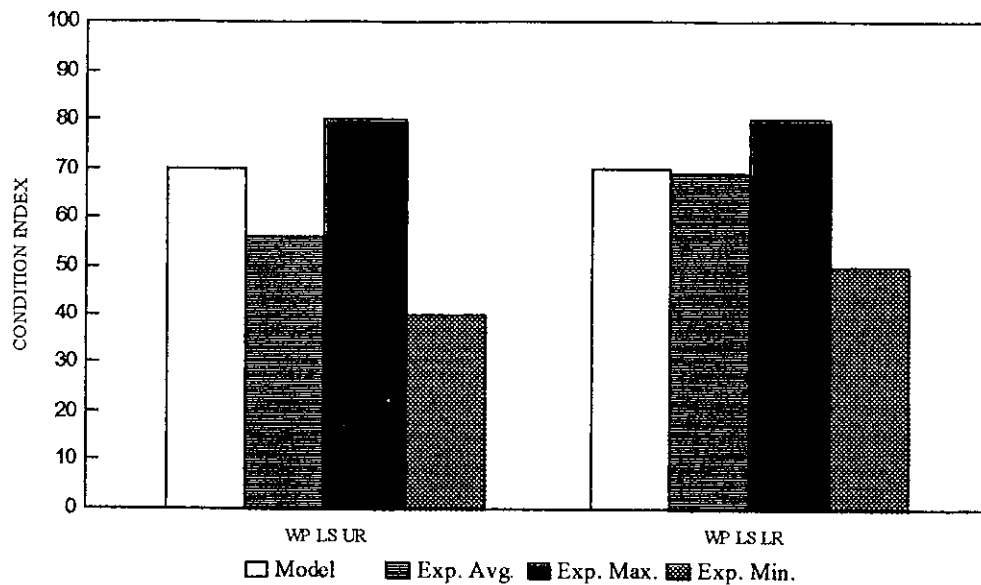

Figure 69. Input Shaft and Hub Movement: Coupling Assembly

Noise, Jumping, Vibration

The noise, jumping, and vibration distress was not calibrated because no noise, jump or vibration in couplings was detected. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or above. The noise, jumping, and vibration

distress was calibrated in the enclosed gear assembly.

Cracks

The cracks distress was not calibrated because there were no cracks observed in the couplings. Hence, the calculated CIs were all 100 and the experts' averaged CIs were 90 or above. Although this distress was not calibrated the experts feel that cracks in the coupling are critical and should be repaired, which corresponds well to the rules for the crack distress.

Corrosion

The corrosion distress was not calibrated because corrosion was not observed in couplings.. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or above. The corrosion distress was calibrated in the strut assembly.

Input Shaft and Hub Movement (Fig. 69)*:*

Figure 69 shows the relative movement between input shaft and hub distress for sector lock gate operating equipment, both located at W.P. Franklin. Relative movement was observed in couplings between the reduction gear box shaft and the cable drum shaft. The experts' average CI for the coupling on the Upper Right Lock Gate is lower than the calculated CI. On the coupling on the Lower Right Lock Gate, the relative movement was less noticeable than on the Upper Right Lock Gate; hence, the experts' average was higher, and matched the calculated CI more closely.

Output Shaft and Hub Movement

The relative movement between output shaft and hub distress was not calibrated because no relative movement between the output shaft and hub in couplings was detected. Hence, the calculated CIs were all 100 and the experts' averaged condition indexes were 90 or

above. The relative movement between input shaft and hub was calibrated.

Assembly CI

The coupling assembly was not one of the assemblies on the inspection form during the field test to the Jacksonville District, therefore, the experts did not subjectively rate the coupling assembly CI for the two cases where relative movement was observed. Although the combined CI could not be calibrated for the coupling assembly, the weighting factors used to calculate the assembly CI were obtained from the experts (Table 22).

CHAPTER 13. SUMMARY AND RECOMMENDATIONS

The inspection and rating procedures described in the previous chapters were kept as simple as possible. Most of the inspection procedures require simple tools such as a tape measure, a dial gauge, a ruler, a caliper, or a pry bar. In all cases the inspection procedure can be accomplished with little interference to normal lock and dam operations.

An inspection form, written to accommodate the inspection procedure, was completed in two sections. On the first, historical information, maintenance history, and current operating characteristics are recorded. Field measurements found during the inspection procedure are recorded in the second.

After field measurements are obtained, computer software will be written to generate the CI for each of the individual distresses and for each assembly. The CI is a number between 0 and 100 which quantifies the current condition of the assembly. The CIs generated with the software are used to determine when the need for maintenance or rehabilitation are required. The rules used for the computation of the CIs were developed with the help of Army Corps of Engineers experts.

CIs are calculated for the individual distresses associated with each assembly. The distress CIs are used to calculate the assembly CIs using the minimum of a weighted average or the individual CI of a distress considered critical to the structural stability of the assembly.

Field tests were conducted at sixteen lock and dam facilities during three trips. Revisions to the inspection and rating procedures as well as to the inspection forms were completed following each of the field tests.

## APPENDIX A: BUSHING WEAR JACKING PROCEDURE

Introduction

The procedure and calculations described in this appendix can be used to further evaluate the bushing wear in large horizontal gears if tipping is evident. When applying the following technique, care must be taken not to apply too much force to the gear. Over loading the gear during the jacking procedure could cause serious damage to the bushing system. This procedure should never be performed on gears with bearings, as damage may occur.

Procedure

Place three dial gages to measure the vertical displacement in the gear (Fig. A1). Place one dial gage at the center of the gear. The remaining two dial gages should be placed at approximately equal distances, X_1 and X_2, from the center of the gear and as close to 180 degrees from each other as possible (Fig. A1). To prevent errors in readings, place all dial gage plungers in the same direction. Record the initial dial readings for all dial gages. Place a jack near one of the dial gages and begin jacking. Precaution should be taken while jacking the gear to insure overloading does not occur. Record the dial gage readings after jacking (Fig. A2). Next release the jack and again take the dial gage readings. Place the jack 180 degrees from the initial position(near the other dial gage) and again jack and record the dial gage readings (Fig. A3). Release the jack and record the dial gage readings.

Calculations

If no bowing occurs in the gear, the total angle of rotation of the gear during the procedure, θ, is found by calculating θ_1 (the angle caused by jacking at position 1) and θ_2 (the
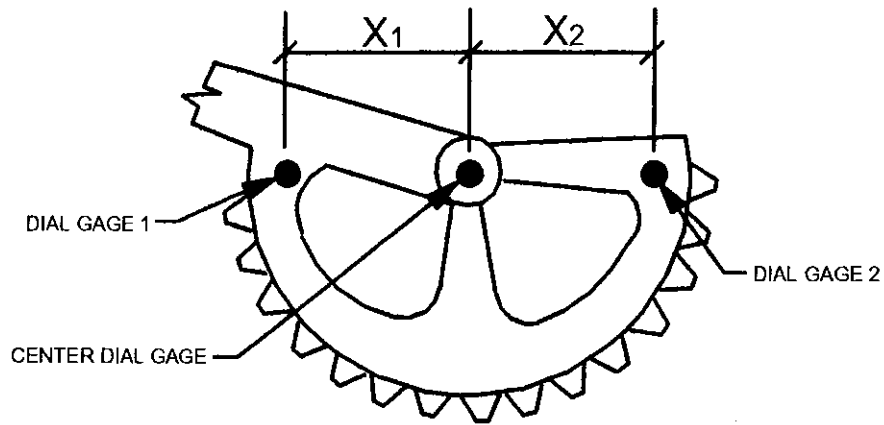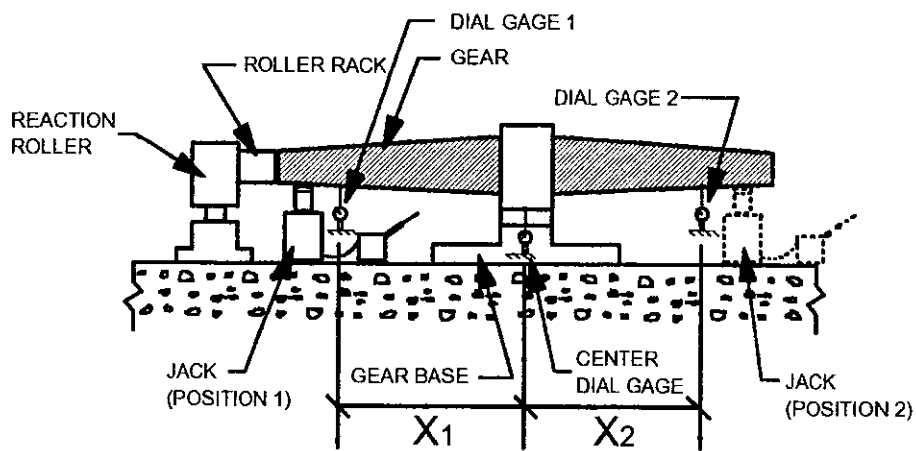
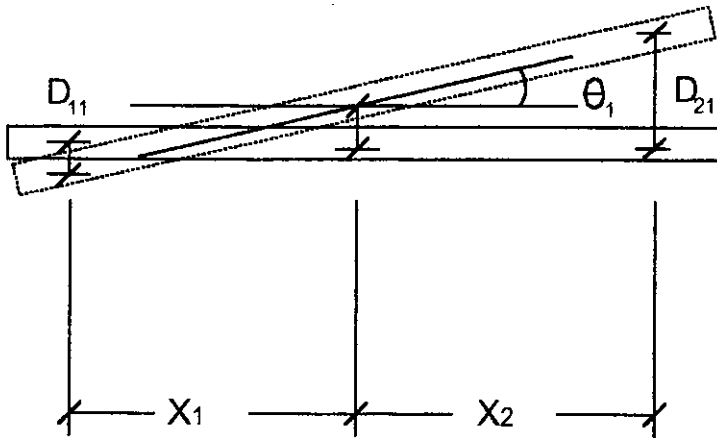Figure A1. Bushing Wear Measurement

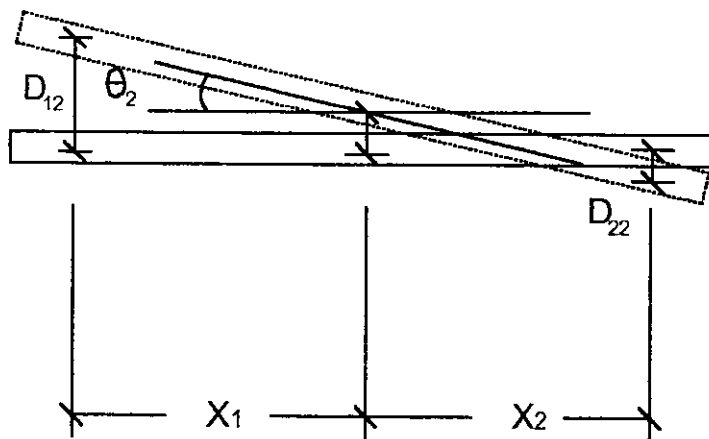**Figure A2. Vertical Displacements When Jacked On Side 1**

Figure A3. Vertical Displacement When Jacked On Side 2

angle caused by jacking at position 2):

$$\theta = \theta_1 + \theta_2$$

The following equation can be used to calculate θ_1

$$\theta_1 = (D_{11} - D_{21})/(X_1 + X_2)$$

where D_{11} is the difference in dial gage 1 readings between the initial gear position and the gear position after the being jacked at position 1

$$D_{11} = \text{Gage 1 reading (initial)} - \text{Gage 1 reading (jacked at 1)}$$

where D_{21} is the difference in dial gage 2 readings between the initial gear position and the gear position after the being jacked at position 1

$$D_{21} = \text{Gage 2 reading (initial)} - \text{Gage 2 reading (jacked at 1)}$$

Similarly, for θ_2

$$\theta_2 = (D_{12} - D_{22})/(X_1 + X_2)$$

where D_{12} is the difference in dial gage 1 readings between the initial gear position and the gear position after the being jacked at position 2

$$D_{12} = \text{Gage 1 reading (initial)} - \text{Gage 1 reading (jacked at 2)}$$

where D_{22} is the difference in dial gage 2 readings between the initial gear position and the gear position after the being jacked at position 2

$$D_{22} = \text{Gage 2 reading (initial)} - \text{Gage 2 reading (jacked at 2)}$$

Assuming that there is no bowing of the gear, the calculated displacement at the center of the gear, $D_{CenterCalculated}$, should be equal to the average of the displacements of the dial gages located 180 degrees from each other, D_1 and D_2:

$$D_{CenterCalculated} = (D_1 + D_2)/2$$

If, however, bowing of the gear does occur, $D_{CenterCalculated}$ will not be equal to the measured

displacement at the center, $D_{CenterMeasured}$ (Fig. A4). To prevent bowing, which introduces

stresses into the gear, the jacking should not continue if $D_{CenterMeasured}$ varies significantly from

$D_{CenterCalculated}$. If bowing has occurred, too much force is being applied to the gear during the

jacking procedure.

Limits

The limiting value for vertical displacement of an exposed gear which rotates on a

bushing is 1/16 in. per foot of gear radius. This corresponds to an angle of rotation of 0.0026
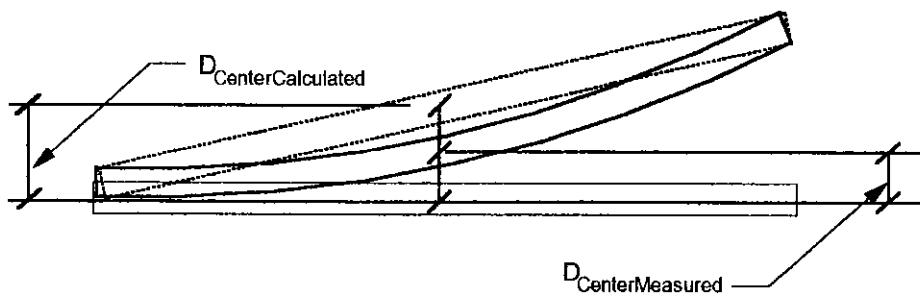
radians or 0.15 degrees.

Figure A4. Displaced Shape of Gear (Bowed and Unbowed)

APPENDIX B: GEAR TOOTH WEAR MEASURING PROCEDURES

Introduction

If the estimated percentage of tooth thickness reduction from the new tooth thickness is 10 percent or greater, the tooth should be measured in order to get a more precise estimate of tooth wear. The following appendix explains tooth thickness measurement techniques.

Gear and Rack Tooth Identification

To inspect and rate gear and rack tooth wear, one needs to be familiar with the nomenclature used in describing gear and rack teeth; definitions for the various tooth relationships are presented in the following paragraphs. Figure B1 shows these relationships graphically.
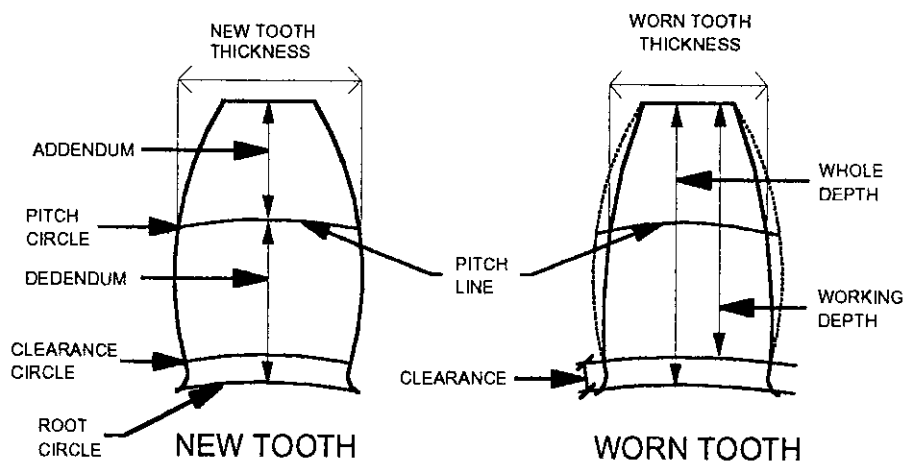

Figure B1. Gear Tooth Dimensions and Wear Measurement

Addendum

The radial distance from the pitch line to the top of the gear.

Dedendum

The radial distance from the pitch line to the root circle.

Clearance

The radial distance from the clearance circle to the root circle.

Whole Depth

The radial distance between the root circle and the top of the gear.

Tooth Thickness

The width of the tooth at the pitch line.

Working depth

The radial distance from the top of the gear to the clearance circle.

Diametral Pitch(DP)

The number of teeth of a gear divided by the diameter of the pitch circle in inches.

Circular Pitch(CP)

The arc distance measured along the pitch circle from a point on one tooth to the corresponding point on the adjacent tooth of the gear. The following equation relates the diametral and circular pitch: $\pi = (CP)(DP)$

Root Circle

The circle drawn through the bottom of the gear tooth.

Clearance Circle

The largest circle centered at the gear center, which is not penetrated by the teeth of the mating gear.

Pitch Circle

The circle on a gear which corresponds to the center of the working depth.

Table B1 shows the relationship between the DP and the addendum, the dedendum, the clearance, the whole depth, and the tooth thickness for six commonly used standard gear profile systems.

Table B1. Gear Tooth Relationships

System	Addendum	Dedendum	Clearance	Whole Depth	Tooth Thickness
14 ½ full-depth involute	1/DP	1.157/DP	0.157/DP	2.157/DP	1.571/DP
14 ½ composite	1/DP	1.157/DP	0.157/DP	2.157/DP	1.571/DP
20 full-depth involute (coarse pitch)	1/DP	1.25/DP	0.25/DP	2.25/DP	1.571/DP
20 full-depth involute (fine pitch)	1/DP	1.2/DP + 0.002 in	0.2/DP + 0.002 in	2.2/DP + 0.002 in	1.571/DP
20 stub-tooth involute	0.8/DP	1/DP	0.2/DP	1.8/DP	1.571/DP
25 full-depth involute	1/DP	1.25/DP	0.25/DP	2.25/DP	1.571/DP

[34]

Procedure 1

Begin by finding the tooth pitch line. In some cases the pitch line is scribed on the tooth during the manufacturing process. If the pitch line can be seen, place a caliper on the top of the tooth with a spacer placed between the caliper and the top of the tooth (Fig. B2). The caliper points should be on the pitch line, one on each side of the tooth. With the caliper now at the correct depth, slide the caliper along the length of the tooth. Find the location of the tooth where the tooth thickness at the pitch line is the smallest. Record this measurement. If the pitch line is not scribed on the tooth, calculate the addendum of the tooth by use of the construction drawings and Table B1. As shown on Figure B1, the addendum is the distance from the top of the tooth to the pitch line. Use the addendum to calculate the
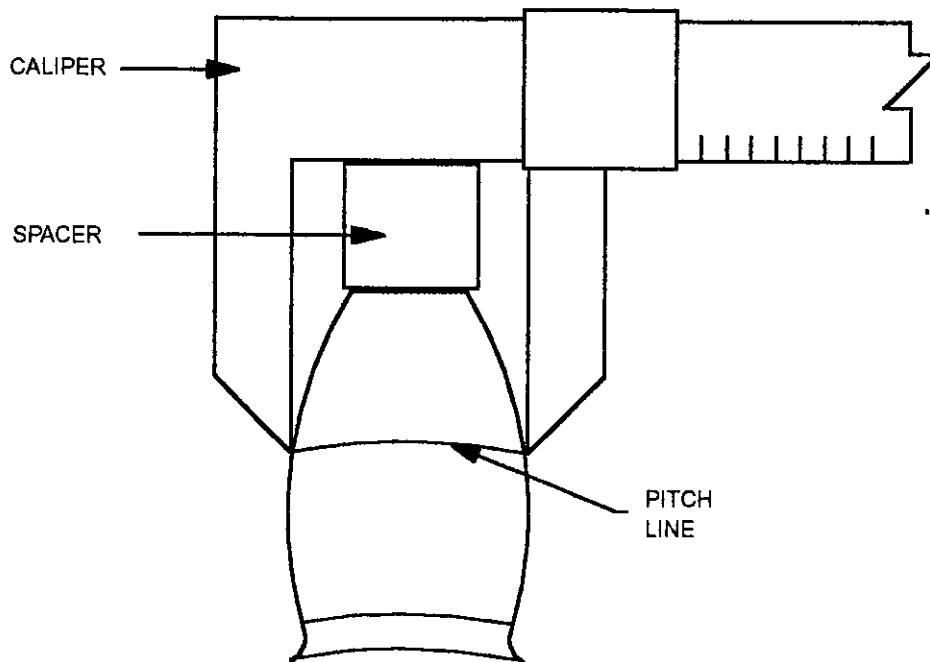

Figure B1. Gear Tooth Wear Measurement: Procedure 1

required spacer thickness. With the spacer in place, follow the same procedure as described above. Next, calculate the new tooth thickness. The new tooth thickness can be calculated from the diametral pitch (DP), which can be found in construction drawings, and Table B1. In some cases the circular pitch (CP) may be listed in the construction drawings instead of the DP. The relationship between the CP and the DP can be found in the gear tooth definitions.

Procedure 2

If gear tooth templates are available during the inspection, place the template in between teeth. With the use of feeler gages, measure the gap between the template and the gear tooth at the pitch line. If the pitch line is not scribed on the tooth, locate the pitch line by calculation of the addendum as described in Procedure 1.

Calculations

If the estimated reduction of tooth thickness is 10% or greater, the measured thickness reduction should be entered in Part 2 of the inspection form for the Exposed Gear Assembly and the Rack Assembly. The percentage of tooth thickness loss can be calculated using the following equation if Procedure 1 was used.

$$\% \text{ thickness reduction} = 1 - \text{(Worn thickness)/(New thickness)}$$

If Procedure 2 was used, the following equation will calculate the percentage of tooth thickness loss.

$$\% \text{ thickness reduction} = \text{(Measured Gap)/(New Thickness)}$$

Examples

Calculation of the Addendum(Location of the Pitch Line)

The pitch line of a tooth can be found by calculating the addendum of the tooth with the use of Table B1. The distance from the top of the tooth to the pitch line is the addendum. A 20 degree involute stub tooth gear with a diametral pitch of 0.75/in. was inspected. The addendum of the tooth is

$$\text{addendum} = (0.8)/(.75/\text{in.}) = 1.067 \text{ in}$$

The distance from the top of this tooth to the pitch line is equal to 1.067 in.

Calculation of New Tooth Thickness

The construction drawings of a gear which is being inspected show P = 1.5/in. From the last column of the table, the tooth thickness for the gear is

$$\text{tooth thickness} = (1.5708)/(1.5/\text{in.}) = 1.0472 \text{ in}$$

Relationship Between CP and DP

Construction drawings show a CP = 3.1416 for an exposed reduction gear. The corresponding DP is

$$DP = (\pi)/(3.1416) = 1$$

Note: For helical and herringbone(double helical)gears the same relationships apply [28]. Helical and herringbone gears are generally coarse pitched, therefore, if this information is not given assume it is coarse pitched. If the pressure angle is not given, the standard helical gear has the same relationships as the 20 degree, coarse pitch gear shown in the table above.

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