Repair, Evaluation, Maintenance, and Rehabilitation Research Program

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REMR Management Systems— Navigation Structures Condition Rating Procedures for Roller Dam Gates

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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 Work Unit 32672, "Development of Uniform Evaluation for Procedures/Condition Index for Deteriorated Structures and Equipment," for which Stuart Foltz is the Principal Investigator. Mr. James E. Crews (CECW-O) is the REMR Technical Monitor for this work.

Mr. David B. Mathis (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James Crews and Dr. Tony C. Liu (CEEC-ED) serve as the REMR Overview Committee; Mr. William F. McCleese, U.S. Army Engineer Waterways Experiment Station, is the REMR Program Manager; Mr. David T. McKay is the Problem Area Leader for the Operations Management problem area.

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, James Stecker, and Timothy Kraal. The study was conducted under the general supervision of Dr. Simon S. Kim, Chief of the Maintenance Management and Preservation Division (FL-P), Infrastructure Laboratory (FL), USACERL. The USACERL technical editor was Linda L. Wheatley, Technical Resources Center.

Special thanks are extended to the following Corps experts who participated in the development of this study: Mr. Richard Atkinson (Rock Island District), Mr. Fred Joers (Rock Island District), Mr. Tom Wirtz (Rock Island District), Mr. Gerald Cohen (St. Paul District), and Mr. Domenico Chianesi (Huntington District).

COL James T. Scott was Commander and Acting Director of USACERL, and Dr. Michael J. O'Connor was Technical Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
square ft	0.0929	square meters

1 Introduction

Background

The U.S. Army Corps of Engineers has designed and constructed many civil works structures such as locks and dams on navigable U.S. inland waterways. As these structures age, the need for maintenance strategies has become increasingly important. The Corps has responded to this need by initiating and developing a Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program.

As part of the REMR program, a research effort concentrating on the inspection and rating of roller dam gates has been developed at Iowa State University (ISU). This research effort has established a consistent means of identifying potential problems for roller dam gates through the use of an inspection procedure. The inspection procedure gathers valuable information to help engineers analyze and evaluate the condition of roller gates and more readily implement necessary maintenance or repairs before severe problems develop.

Being able to rely on roller dam gates as operating components of a navigation dam or a power dam facility is essential. Roller dam gates are critical for maintaining the upper pool and for use in flood control at lock and power dam facilities. If a dam gate fails, causing the loss of pool, navigation along an entire stretch of river may be at a standstill until the pool is restored. In the case of a power dam project, loss of head results in decreased power generation capacity.

Objective

The objective of this project was to develop an inspection and rating procedure that describes the current condition of roller dam gates in a uniform manner.

Mode of Technology Transfer

It is recommended that the inspection procedures developed in this study for roller dam gates be incorporated into Engineering Regulation (ER) 1110-2-100, *Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures*.

Overview and Approach

The concepts put forth in this report for the inspection and rating of roller dam gates stem from work in similar projects for steel sheet pile structures (Greimann and Stecker 1989, 1990), miter lock gates (Greimann, Stecker, and Rens 1990), sector gates (Greimann, Stecker, and Rens 1993), tainter and butterfly valves (Greimann, Stecker, and Veenestra 1994), and tainter dam and lock gates (Greimann, Stecker, and Nop 1995). Basic ideas such as condition indexes, safety and serviceability, quantified distresses by field measurements, and limiting values of distresses were refined as the investigation of new structures broadened. Several enhancements have been developed and applied to roller dam gates.

The investigation by the project team consisted of meetings, site visits, and field investigations with Corps of Engineers personnel at several lock and dam facilities. Preliminary roller dam gate field visits and meetings took place at the Mississippi River Lock and Dams: 5A, 14, 15, 16, 17, 20, and 21. At these meetings and site visits, Corps experts provided valuable insight regarding the critical components and problems associated with the operation and repair of roller dam gates. They suggested ways of quantifying the condition of roller dam gates by relating problems or distresses to the overall condition of the gates. Table 1 lists the distresses and a brief description of each. Using the experts' comments, the project team formulated an inspection procedure and a tentative set of rating rules.

Table 1. Roller dam gate distresses.

Distress	
Noise/jump/vibration	Abnormal noise, jumping, or vibration while operating the gate
Vibration with flow	Vibration of gate while water flows under or over it
Torsional misalignment	Twisting of the gate due to torsional forces present under normal operation
Rack deterioration	Deterioration of the rack components and anchorage connections
Rim deterioration	Deterioration of the rim components and connections
Seal/end shield damage	Damage to the side or bottom seals or the end shield
Cracks	Breaks in structural steel components
Dents	Disfiguration of structural steel components
Corrosion/erosion	Loss of steel due to interaction with the environment
Downstream deflection	Flexural deflection of the gate in the downstream direction

Field Inspection

Figure 1 illustrates the inspection and rating procedure. A field inspection is a means of gathering data for any particular roller dam gate. The first two pages of the inspection form (pp 9 and 11 of this report) are used to record descriptive data, such as the location and the type of gate, general component information, and maintenance history. Additional pages provide space for recording field measurements that relate to the various distresses. The field measurement data is used to assess the current state of the structure. This is accomplished by entering all the information collected on the inspection form into a data file on a microcomputer that performs all the calculations necessary to obtain a condition index (CI) for the gate.

Field Test

A field test consists of performing the field inspection procedure at several lock and dam facilities. The field test serves two purposes: First, to determine the

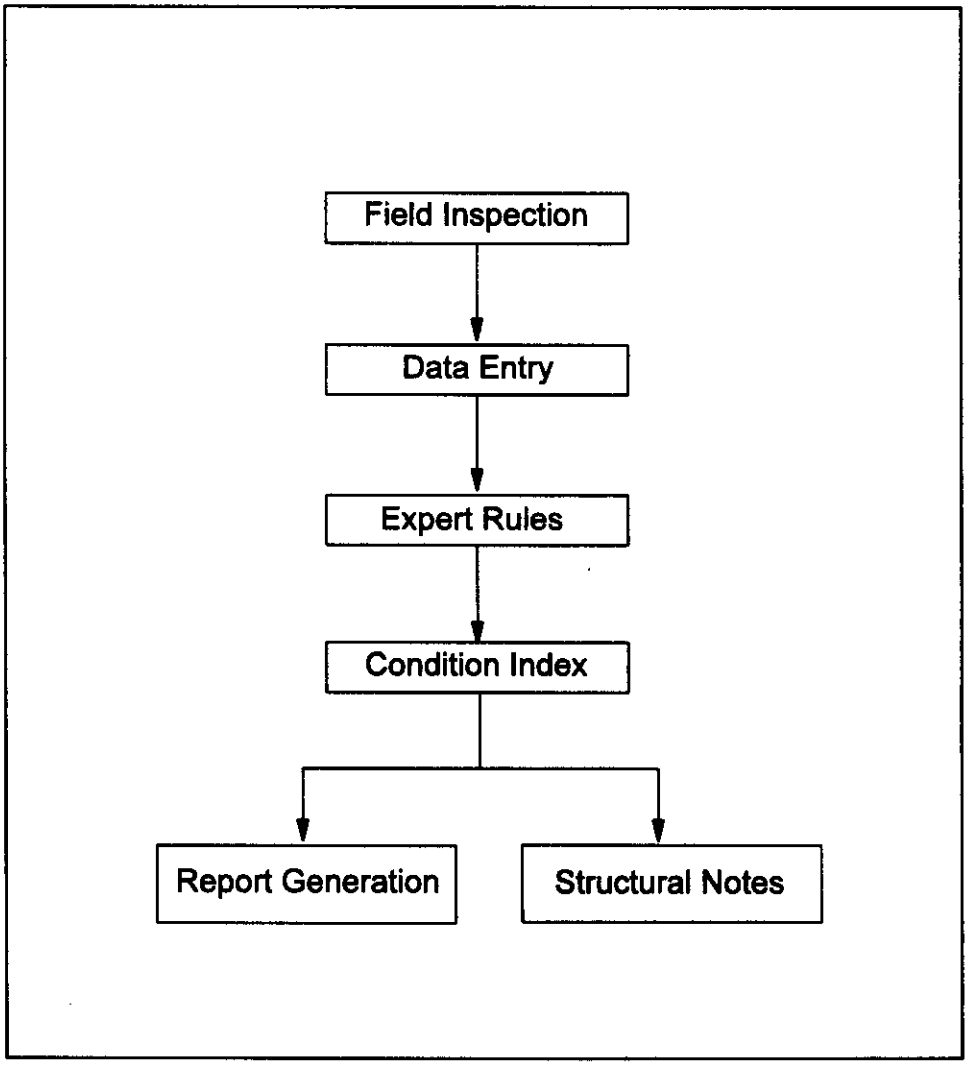

Figure 1. Inspection and rating procedure

plausibility of the field inspection procedure, and second, to compare and calibrate the CI rating rule results with the experts' opinions to ensure that the current condition of a gate is reflected. While extensive testing was performed, a complete field test with calibration of the rating rules was not conducted. However, the project team and Corps experts performed inspections at several sites in the Rock Island District. The problems encountered in the inspection procedure and the discrepancies between the experts' opinions and the rating rules were addressed.

Condition Index

A CI is the numerical measure used to rate the current state of a gate. The CI has two purposes: First, the CI values serve as a planning tool meant to focus management attention on those roller dam gates most likely to warrant immediate repair or further evaluation. Second, the CI values can be used to monitor change in general condition over time and can serve as an approximate comparison of the condition of different structures. One of the goals of this research was to define a CI that uniformly and consistently ranks the condition of roller dam gates.

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 structure. For management purposes, the CI scale is also calibrated to group structures into three basic categories or zones (Table 2).

Table 2. Condition index scales and zones.

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

Roller Gate Description

Roller dam gates are used to control the upper pool elevation at a lock and dam structure. The basic purpose of a roller gate is to control the amount of water that flows from the upper pool to the lower pool. This is accomplished by lifting or lowering the roller gate to suitable elevations. A lifting chain attached to one end of the roller gate forces the gate to roll up an inclined rack attached to the pier. To lower the gate, the lifting chain is let out and the gate rolls down the inclined rack into the river. Openings in the gate skin plate allow the gate to fill with water so that it does not become buoyant. Figure 2 is an overall view of a submersible roller dam gate.

Roller Gate Component Identification

To inspect and rate roller dam gates requires familiarity with the configurations and components of such structures. Definitions and sketches of these components are presented in the following paragraphs:

Upper apron: Many submersible gates have an apron on top of the drum called an upper apron. The upper apron prevents flow over the top of the roller gate when the gate is in the closed position. When a gate is submerged water flows over the upper apron (Figures 2 and 3).

Lower apron: The lower apron is the noncylindrical portion of the gate that prevents flow under the roller gate (Figures 3 through 6).

Bottom seal: The bottom seal is the interface between the lower apron and the concrete sill (Figures 4 and 6).

Drum: The cylindrical portion of the gate between the end drums of the driven and nondriven end is the drum, which is composed of several curved steel plates fastened together (Figure 5).

End drum: The end drum is the portion of the gate between the end disc and the first circumferential splice in the skin plate. In practice, it is more common to refer to the portion of the gate from the end disc to the load disc as the end drum (Figures 5, 7, and 8).

End disc: The end disc encloses the cylindrical end drum, there is one end disc on the driven end and one on the nondriven end of the gate (Figures 7 and 8).

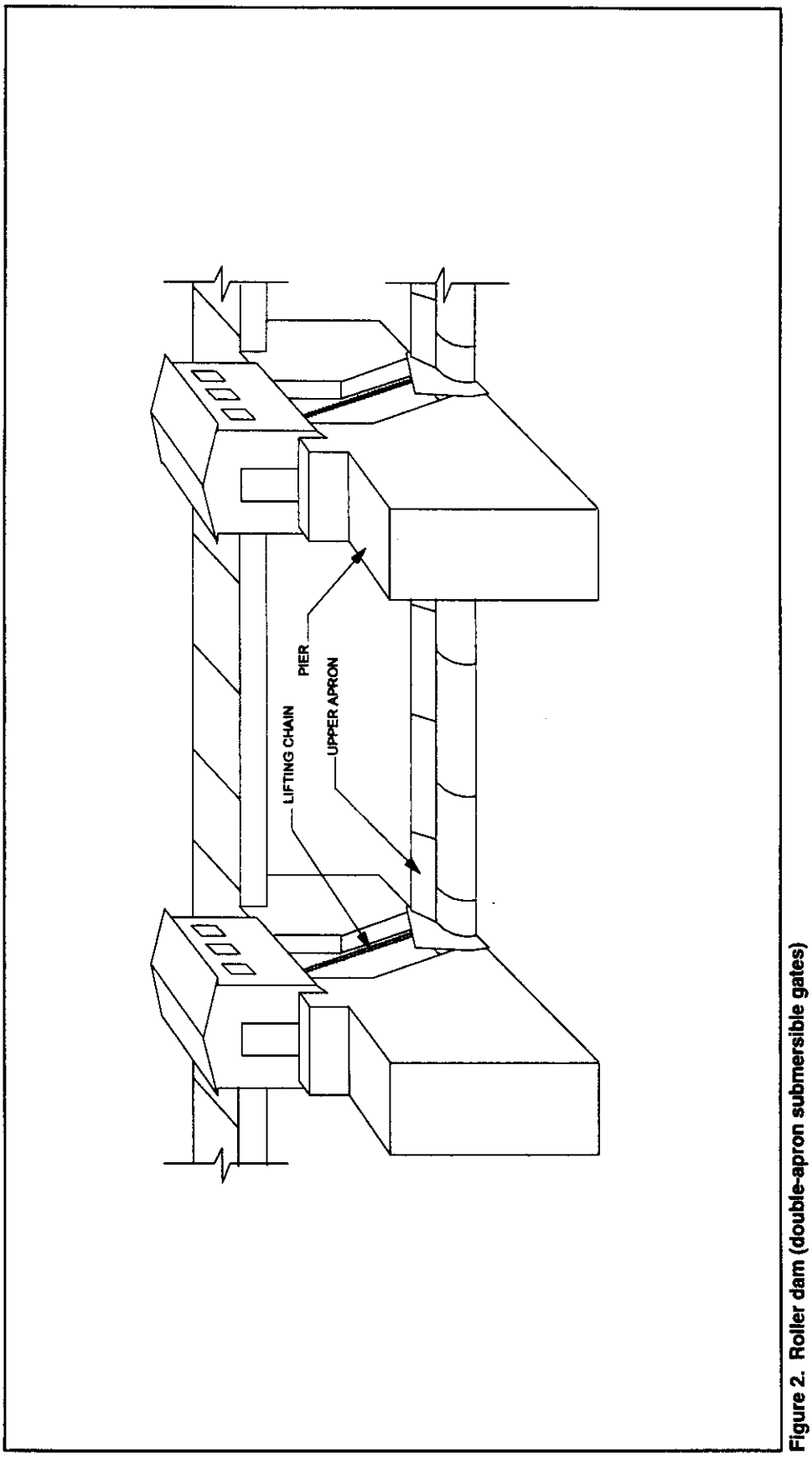

Figure 2. Roller dam (double-apron submersible gates)

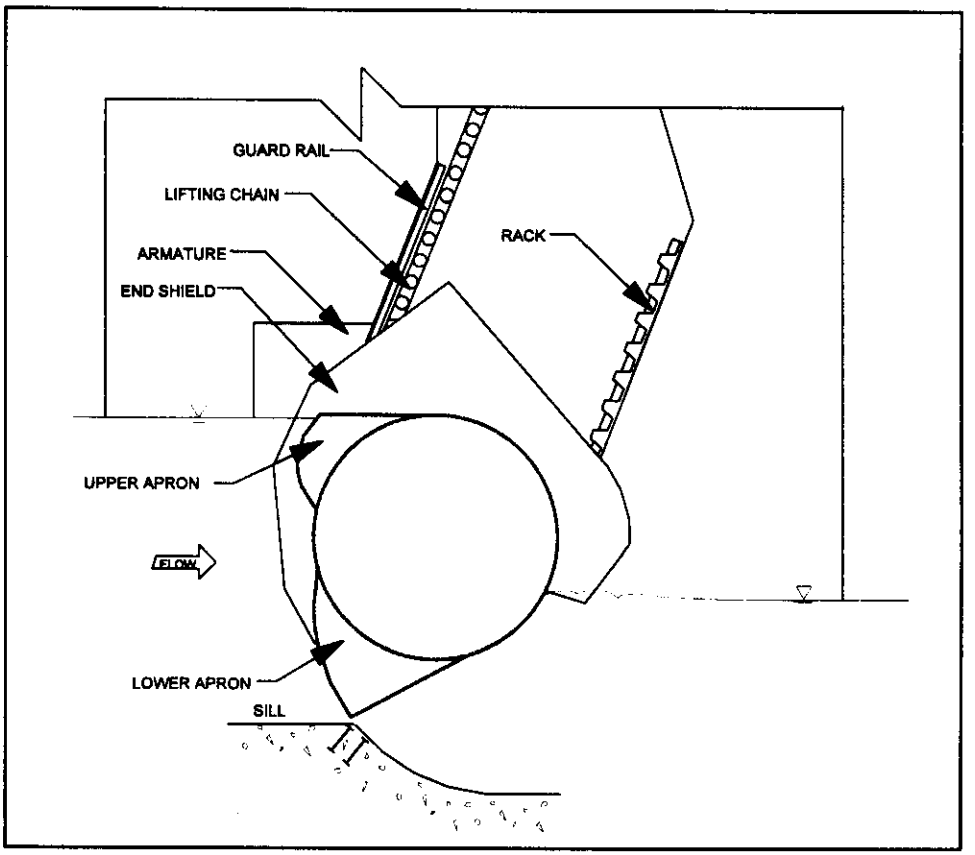

Figure 3. Roller dam gate (double-apron submersible gate)

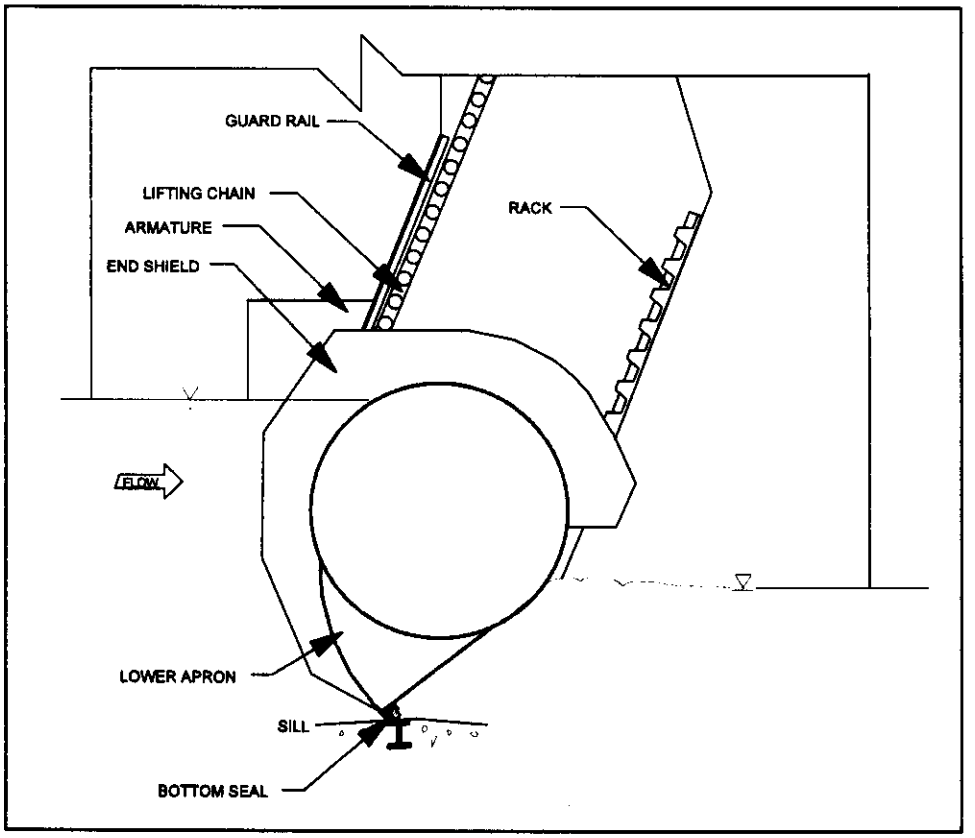

Figure 4. Roller dam gate (single-apron nonsubmersible gate)

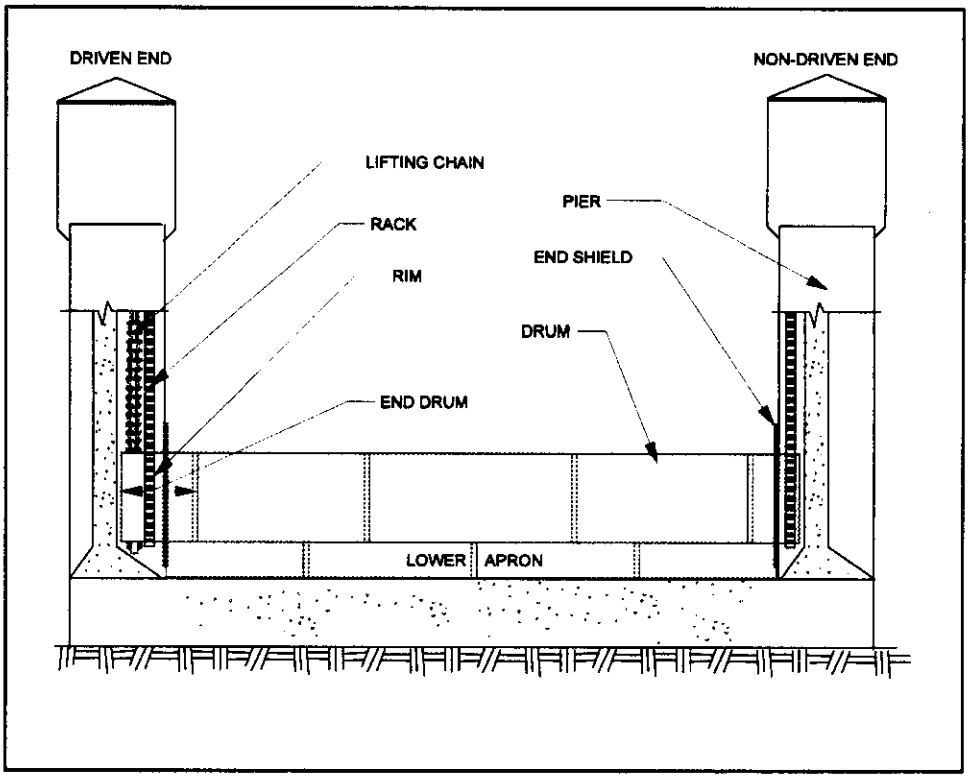

Figure 5. Roller dam gate (single-apron nonsubmersible, all parts except lifting chain common to both ends)

Skin plate: The plate-steel that covers the cylindrical drum, end drums, and the apron(s) of the roller gate providing stiffness to the structure as it dams the water and transfers load to the internal framing (Figures 6 and 7).

Purlins: Purlins frame the gate longitudinally, supporting the drum skin plate. Purlins span between the internal trusses (Figure 6).

Intermediate truss: Internal trusses support the purlins bracing the roller gate transversely (Figure 6).

Load disc: The load disc is inside the end drum of the gate and transfers load from the internal framing of the gate to the rim. Both ends of the roller gate have a load disc (Figures 7, 8, and 9).

Rim: The rim is part of the gate and has a rim track and rim teeth that transfer load from the load disc to the rack track and rack teeth, respectively (Figures 5, 7, 8, and 9).

Track extension: The track extension is a segmented casting that extends the rim track the complete circumference of the gate (Figures 7, 8, and 9).

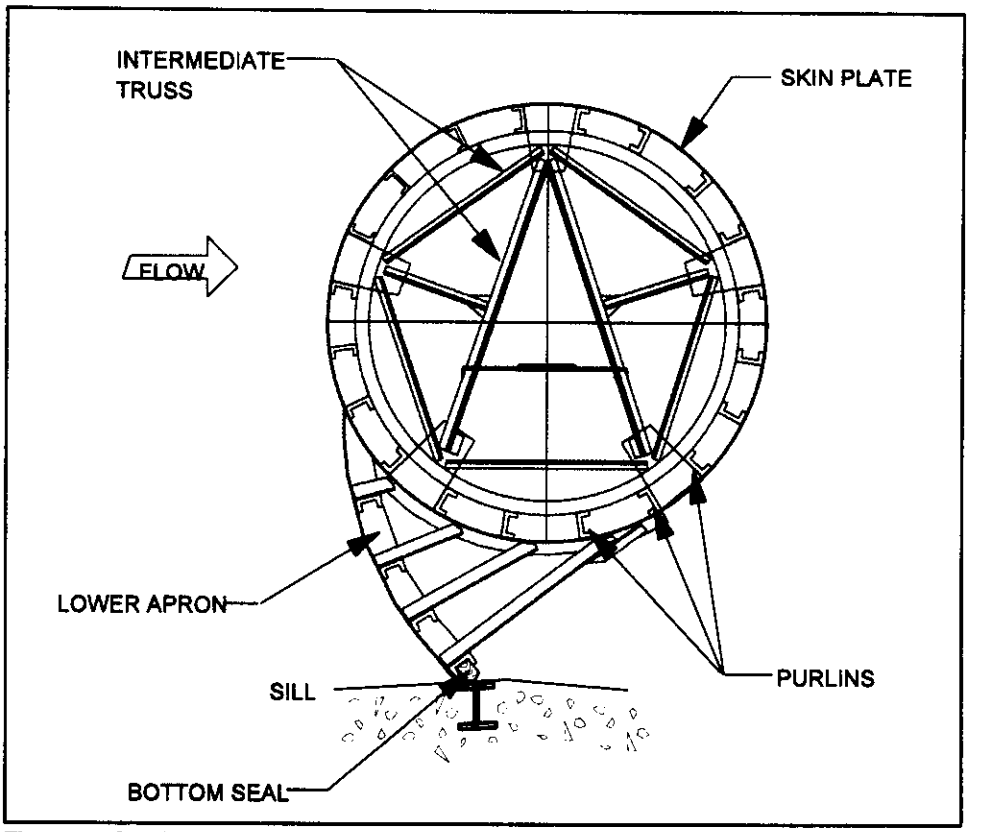

Figure 6. Section through drum (single-apron nonsubmersible)

Rack: The rack transfers load from the gate to the pier utilizing rack teeth and a rack track similar to the rim teeth and rim track. The sloping rack is supported by a ledge in the pier (Figures 3, 4, 5, 8, and 9).

Guard rail: Located on the upstream portion of the pier, the guard rail is a matching surface for the rim track. The guard rail does not have teeth like the rack and the rim (Figures 3, 4, 7, 8, and 9).

Pier: Concrete piers support the roller gate racks on both driven and non-driven ends. The roller gate operating equipment is housed in the pier (Figures 2, 5, 7, and 8).

Armature: The armature is the steel plate fastened to the pier upstream of the gate. Side seals fastened to the end shields contact the armature (Figures 3, 4, 7, and 8). **Side seals:** Side seals are fastened to the end shields and help prevent flow between the gate and the pier. Side seals may be constructed of timber or rubber (Figures 7 and 8).

End shield: The end shield prevents debris from collecting between the roller gate end drum and the pier (Figures 3, 4, 5, 7, and 8).

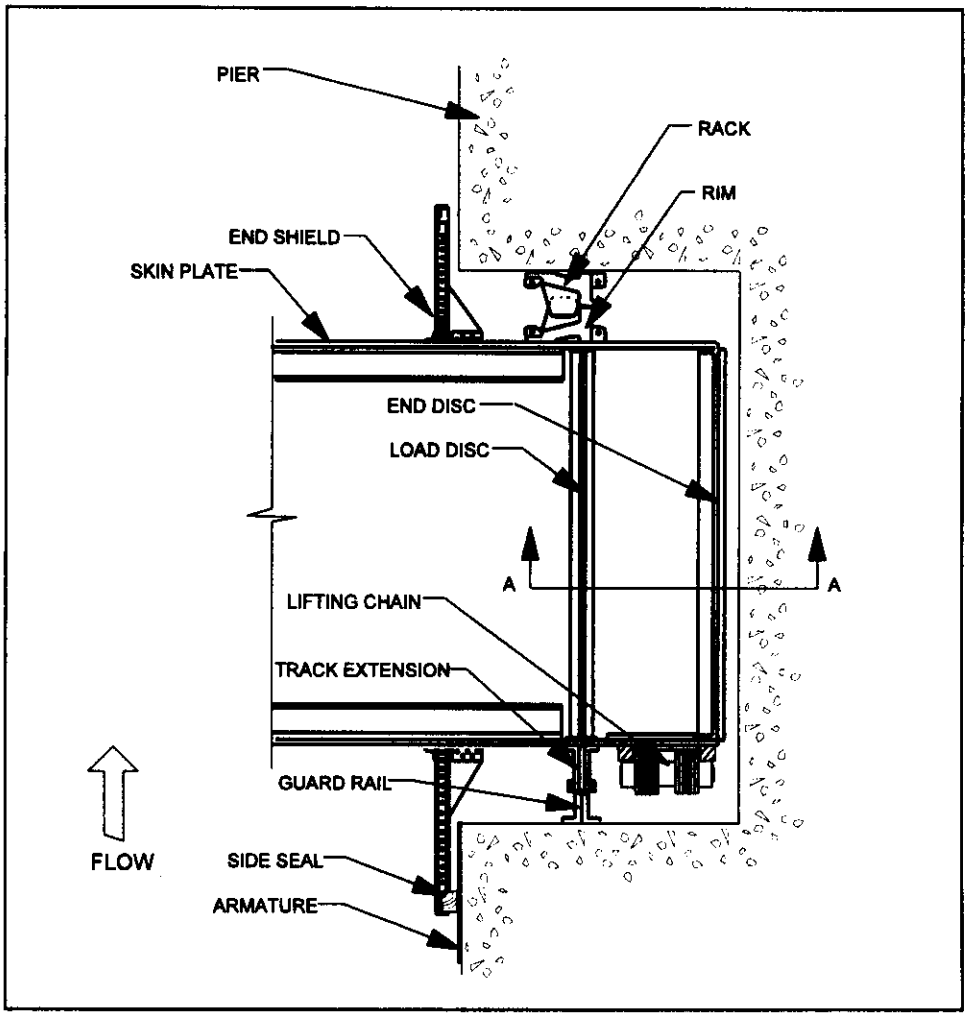

Figure 7a. Section of the driven end drum.

Lifting chain: The lifting chain connects the operating machinery with the gate. It moves the gate between its open and closed positions. The lifting chain is considered part of the operating equipment and not part of this inspection and rating procedure (Figures 2 through 5).

Chain guides: These components are semicircumferential supports fastened to the gate that keep the lifting chain from contacting the skin plate (Figure 7).

Chain anchor: The lifting chain is connected to the chain anchor. Most of the chain anchor is visible from the exterior of the roller gate (Figure 7).

Chain anchor segment: The chain anchor segment is in the end drum of the driven end of the gate and connects the chain anchor to the gate, transferring the lifting force from the chain to the gate using a steel web plate (Figure 7).

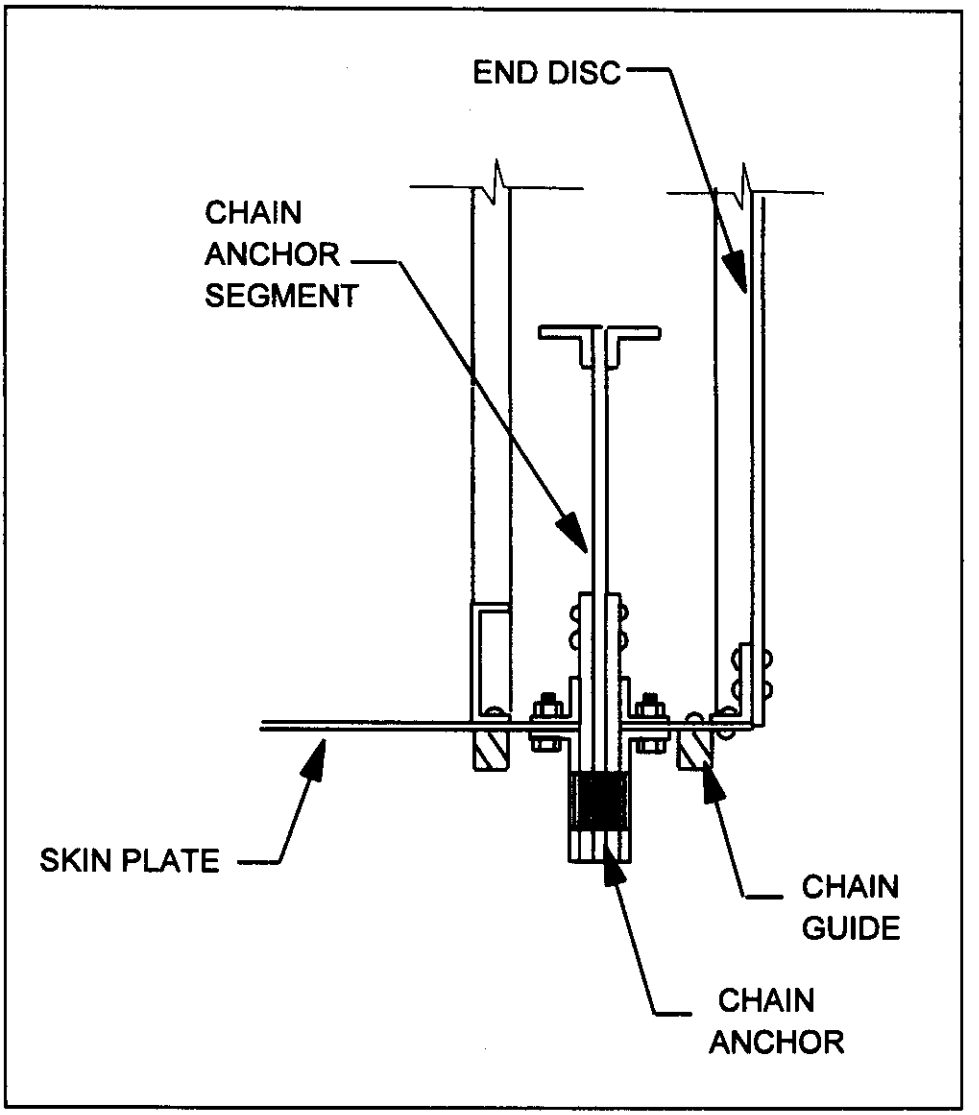

Figure 7b. Section A-A through driven end drum

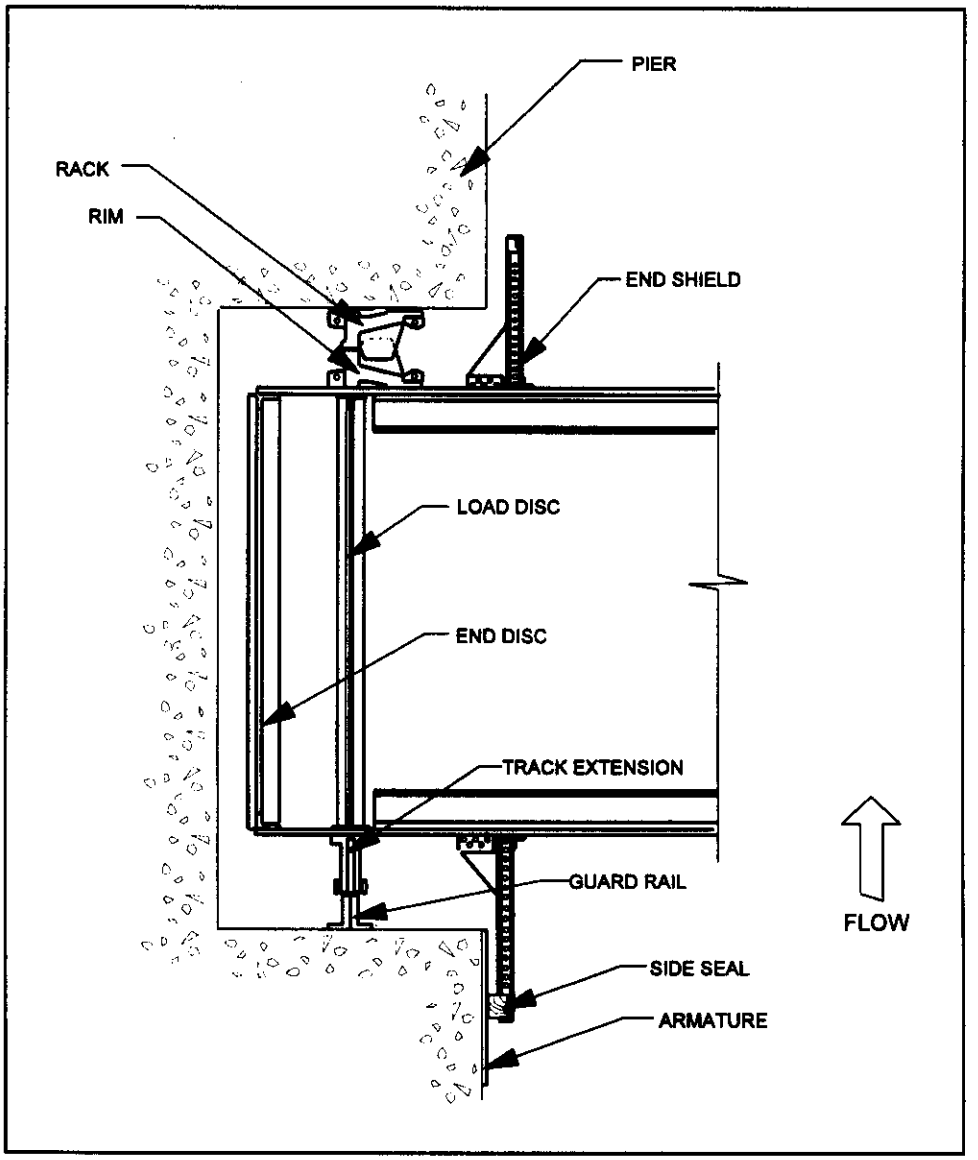

Figure 8. Section of the nondriven end drum

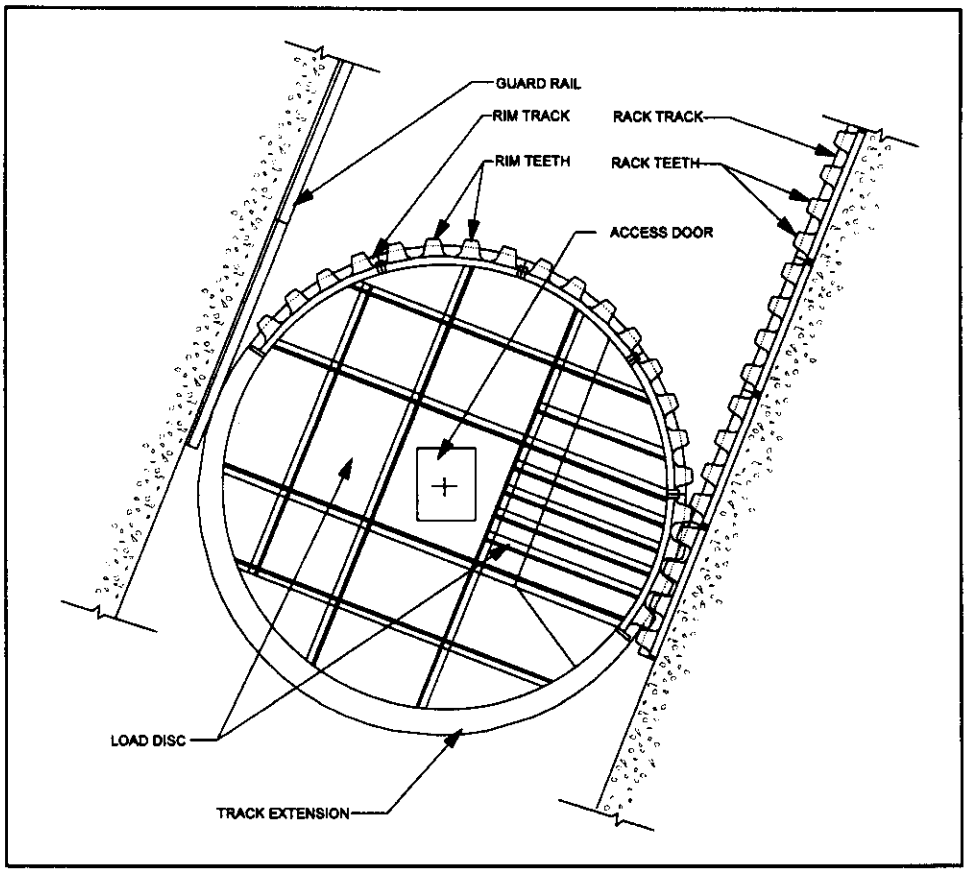

Figure 9. Load disc

2 Field Inspection

Inspection Procedure Development

To be effective, an inspection procedure for roller dam gates must accomplish at least three goals: (1) It must be as objective as possible and give consistent results regardless of location, type of gate, or inspector, (2) it must be an accurate assessment of the structural condition of the roller gate being inspected, and (3) it must be easy to learn and perform.

To be objective and consistent, the inspection procedure must consider many factors affecting the inspection procedure and results. Roller dam gates have different configurations and function under different conditions. The geometry and dimensions of roller dam gates can also differ greatly. For example, some roller dam gates may have a lower apron only, while many have both lower and upper aprons. Many gates are submersible and, therefore, are operated under different conditions than nonsubmersible gates. Projects that consider leakage control critical are treated differently than projects that do not. For example, leakage control may be considered critical at sites that have electric power generating plants. Another complicating factor is the amount of lift[1] at the time of the inspection. Lift varies from site to site and day to day and the inspection procedure must account for these different gate loading situations. All these factors affect the behavior of a roller gate and must be considered to maintain a uniform inspection and rating procedure for all roller dam gates.

An inspection procedure can accurately rate the condition of roller dam gates if, and only if, it considers the various forces on the gate. For example, the effect of ice or debris can be significant, causing damage to the skin plate, end discs, end shields, and seals. Therefore, the inspection procedure must have a means to record any such damage so an accurate rating of the gate can be made.

Despite complications and requirements, the inspection procedure must not become so detailed or lengthy that it is impractical. No specific engineering training or experience should be required to perform the inspection, and all data collected should be easily obtained. Measurements should be simple to perform, using tape measures and rulers. Above all, the means of gathering data must not endanger the people involved. Addressing these types of considerations has

[1] Lift is the difference between elevations in the upper pool and the lower pool.

resulted in the inspection procedure for roller dam gates described in the remainder of this chapter.

Overview of Inspection Procedure

Corps Districts often schedule annual inspections, usually performed while the gate is under normal operating conditions. No special provisions are made to bulkhead the gate or to remove it from operation for a detailed inspection. A gate is bulkheaded by dropping steel stop logs (bulkheads) upstream of the gate and is out of operation when rolled up out of the river. Although inspections performed under bulkheaded conditions may be preferred to those performed under normal operating conditions, they are more costly. However, bulkheads are placed periodically, and a more detailed inspection is made of the gate's condition. During this type of inspection, necessary maintenance may be performed on the damaged or deteriorating gates. Periodic Inspections of this nature occur about every 5 years.

To complement established inspection scheduling, the project team developed an inspection procedure that adapts to normal operation, out-of-operation, and bulkheaded conditions. The inspection can then be performed under whatever conditions are available. Because the initial inspection is likely to be done under normal operating conditions, certain parts of the roller dam gate can be only partially inspected. For example, to fully inspect the rim for damage and deterioration, the gate has to be either taken out of operation, bulkheaded, or dewatered. Table 3

Table 3. Required inspection conditions

DISTRESS	INSPECTION CONDITIONS		
	Normal Operation	Out of Operation	Bulkheaded
Noise, jump, and vibration	F	N	N
Vibration with flow	F	N	N
Torsional misalignment	F	N	N
Rack deterioration	P	P	P
Rim deterioration	P	F	F
Seals/end shield damage	P	F	F
Cracks	P	F	F
Dents	P	F	F
Corrosion, erosion	P	F	F
Downstream deflection	N	N	F

F - full inspection possible
N - no inspection possible
P - partial inspection possible

lists distresses and the level of inspection that can be accomplished for each distress. Even though the inspection procedure will generally be completed under normal operating conditions, inspection under bulkheaded conditions will give a more accurate evaluation of the gate condition. Although not as comprehensive as a bulkheaded inspection, out-of-operation conditions can be used for some of the inspection that cannot be accomplished under normal operating conditions.

Overview of the Inspection Form

The inspection form (beginning on p 18) for roller dam gates has been designed to provide flexibility in documenting a variety of field conditions within one standard form. The first two pages of the form ask for historical and other factual information. Specific information such as the rim radius should come from construction drawings. Therefore, these pages should be completed before the field inspection. The remaining five pages of the form are completed in the field. The following paragraphs describe the inspection form structure in more detail.

Historical Information

Historical information related to the roller gate structure is recorded on pages 1 and 2 of the inspection form. Project reference data is recorded to identify and locate the specific structure. Conditions under which the inspection will be performed and information categorizing the structure into a particular type and function are requested. Some facts such as gate dimensions and head conditions are used to sort through the expert rules in the evaluation process and calculation of CIs. Entries for historical descriptions of maintenance, modifications, and inspections are also provided on page 2 for reference only.

Field Measurements

Pages 3 through 7 of the inspection form are used to record observations and field measurements, including rack deterioration, cracks, dents, corrosion, torsional misalignment, noises, and vibrations. The expert rules described in Chapter 3 use these field measurements to determine the CI for roller dam gates.

General Notes

The inspection form for roller dam gates is shown on the next eight lefthand pages. More specific explanations of each portion of the inspection form are provided on facing pages. These commentary pages can be used as an aid to acquiring the appropriate information while filling out the inspection form. Figures 10–17 (following the inspection form) illustrate how some of the measurements are made.

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U.S. ARMY CORPS OF ENGINEERS **PAGE 1**
ROLLER DAM GATE STRUCTURE INSPECTION

NAME OF CIVIL WORKS PROJECT:

_____

_____

LOCATION OF CIVIL WORKS PROJECT: (1.Body of water, 2.Nearest town)

1. _____
2. _____

GATE IDENTIFICATION NUMBER: _____

FIRST INSPECTION DATE OF RECORD: _____

COMPLETE LIST OF INSPECTION DATE(S):

DATE PAGE 3 WAS COMPLETED (NORMAL OPERATING): _____
INSPECTED BY: _____

DATE PAGES 4,5,6 WERE COMPLETED: _____
CONDITIONS OF INSPECTION:
(1)BULKHEADED OR (2)OUT OF OPERATION (no.) _____
INSPECTED BY: _____

DATE PAGE 7 WAS COMPLETED (BULKHEADED): _____
INSPECTED BY: _____

TYPE OF GATE:
1. SUBMERSIBLE
2. NON-SUBMERSIBLE (no.) _____

NUMBER OF APRONS:
1. LOWER APRON ONLY
2. UPPER AND LOWER APRONS (no.) _____

WILL INTERIOR OF GATE BE ACCESSED?
1. YES
2. NO (no.) _____

LENGTH OF GATE: (ft) _____
GATE HEIGHT: (ft) _____
DRUM RADIUS: (in.) _____
RIM RADIUS: (in.) _____

DESIGN UPPER POOL ELEVATION: (ft) _____
DESIGN LOWER POOL ELEVATION: (ft) _____
SILL ELEVATION: (ft) _____

DO YOU ROUTINELY BULKHEAD THE GATE? Y N
IF YES, WHAT YEAR WAS THE GATE LAST BULKHEADED? _____
INTERVAL PERIOD: _____
CONSTRUCTION DATE: _____

Page 1 Comments: Historical or General Data

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

Data blanks on page 1 prefaced by (no.)___ must be recorded as numbers.

Enter in the NAME of the Corps of Engineers Project Title.

Indicate the BODY OF WATER and NEAREST TOWN.

Indicate the GATE IDENTIFICATION NUMBER. If a numbering scheme exists use it, otherwise number all gates from left to right looking downstream.

Record the FIRST INSPECTION DATE OF RECORD that is the earliest DATE that completion of this form began.

Give a summarized listing of INSPECTION DATE(S) and inspectors for the three PAGE groupings that correspond to up to three different DATES for the INSPECTION. The first grouping is PAGE 3 and must be COMPLETED under NORMAL OPERATING conditions. A NORMAL OPERATING condition refers to the usual status of the gate structure. The second grouping is PAGES 4, 5, and 6 and can be COMPLETED under BULKHEADED OR OUT-OF-OPERATION CONDITIONS. BULKHEADED conditions imply that bulkheads will be placed to remove head or load from the gate. OUT OF OPERATION means that the gate has been completely removed from the river (for example, during high river levels of spring). The third and final grouping is PAGE 7, which must be completed under BULKHEADED conditions.

Indicate the TYPE OF GATE by recording the appropriate number. Indicate the NUMBER OF gate APRONS. Indicate whether or not the INTERIOR OF the GATE WILL BE ACCESSED by recording the appropriate number.

Enter the LENGTH of the gate. The LENGTH is the distance between the pier faces. Enter the overall HEIGHT of the gate, which is the maximum amount of upstream head the gate can hold back. If for example the gate is 100 ft x 20 ft, then the LENGTH is 100 ft and the HEIGHT is 20 ft.

Enter the DRUM RADIUS of the roller gate, which is the outside radius of the cylindrical portion of the gate. Also enter the RIM RADIUS, which is the rolling radius of the gate.

Enter the DESIGN UPPER POOL and LOWER POOL ELEVATIONS. Enter the SILL ELEVATION. These elevations are referenced to mean sea level. The inspection conditions are compared with the design conditions.

The YEAR the gate was last BULKHEADED and the CONSTRUCTION DATE may be important for reference.

ROLLER DAM GATE STRUCTURE INSPECTION

IS THE ORIGINAL GATE CURRENTLY IN PLACE? Y N

IF SO, WHAT YEAR WAS IT PUT INTO OPERATION? _____
IF NOT, IDENTIFY CURRENT GATE HISTORY: _____

ARE DRAWINGS AVAILABLE FOR THE GATE IN PLACE? Y N

ARE THE DRAWINGS INCLUDED WITH THIS FILE? Y N

PAST 10-YEAR HISTORY

MAJOR MAINTENANCE, REPAIRS, OR OTHER MODIFICATIONS

	DATE	DESCRIPTION
(1):		
(2):		
(3):		
(4):		

PREVIOUS INSPECTIONS OR STRUCTURAL REVIEWS (attach available copies)

	DATE	DESCRIPTION
(1):		
(2):		
(3):		
(4):		

CONDITION OF LIFTING EQUIPMENT: _____

OTHER COMMENTS: _____

Page 2 Comments: Historical or General Data

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

Gates are sometimes replaced or removed during rehabilitation. It is important for later reference to record the history of the gate that is currently in place.

Enter MAJOR MAINTENANCE, REPAIRS, OR OTHER MODIFICATIONS performed on the gate within the last 10 years.

Enter PREVIOUS INSPECTION information for reference purposes.

Record the CONDITION OF LIFTING EQUIPMENT or reference appropriate operating equipment inspection form(s).

ROLLER DAM GATE STRUCTURE INSPECTION

COMPLETED UNDER NORMAL OPERATING CONDITIONS

INSPECTION DATE: _____
INSPECTED BY: _____
CURRENT UPPER POOL ELEVATION: (ft) _____
CURRENT LOWER POOL ELEVATION: (ft) _____

OPENING AND CLOSING OF THE GATE

		IS IT NORMAL?	GATE OPENING
NOISE?	Y N	Y N	_____
JUMPING?	Y N	Y N	_____
VIBRATION?	Y N	Y N	_____

VIBRATION WITH FLOW

		GATE OPENING
GATE VIBRATION (LEVEL 0, 1, 2, 3, or 4):	_____	_____

CAN VIBRATION BE ELIMINATED BY GATE ADJUSTMENT? Y N

TORSIONAL MISALIGNMENT

PROJECTION DEVICE OFFSET DISTANCE ON BOTH ENDS (in.) _____

DEVICES ARE OFFSET UPSTREAM OF HIGH POINT OF GATE? Y N

PROJECTION DEVICE HEIGHT OFF GATE ON BOTH ENDS (in.) _____

DISTANCE BETWEEN MARKS AT 6-ft OPEN AND 0-ft OPEN (FOR NONSUBMERSIBLE GATE—CLOSED POSITION WITH CHAIN TIGHT)

DRIVEN END (in.)	NON-DRIVEN END (in.)
_____	_____

Page 3 Comments: Field data

Completed at-site inspection under NORMAL OPERATING CONDITIONS.

Record the INSPECTION DATE, name of inspector(s), and the CURRENT UPPER and LOWER POOL ELEVATIONS relative to mean sea level.

OPENING AND CLOSING OF THE GATE: Open the gate 2 ft and record the occurrence of any NOISE, JUMPING, or VIBRATION of the gate. Observe the gate during closing also. If any of the three exist, indicate whether or not it is NORMAL. Also record the GATE OPENING that the NOISE, JUMP, or VIBRATION occurred (- for submersed). For submersible gates, repeat the above procedure for an additional range of gate openings. Observe the gate during operation between openings of 0 ft and submersed to -4 ft or as deep as possible if gate does not submerse to -4 ft.

VIBRATION WITH FLOW: With the gate open 2 ft, indicate the LEVEL of GATE VIBRATION observed using the scale below. For a submersible gate, also indicate the LEVEL of GATE VIBRATION at a gate opening of -4 ft.

Level	Description of Vibration Level
0	No vibration
1	Feel with finger tips on gate or end shields, hear humming noise
2	Large ripples (1/2 in. high) on upper pool
3	Rattles end shields, and bracing, etc.
4	Vibrates or shakes pier

If vibration exists, determine whether it can be ELIMINATED with ADJUSTMENT of the gate position.

TORSIONAL MISALIGNMENT: With the gate in the CLOSED position (chain still tight for a nonsubmersible gate), securely fasten projection devices to both end drums as near to the pier walls as possible. The devices should be placed upstream of the high point. They should also avoid obstructions such as the access ladder or recess in concrete pier on both ends of the gate. Project a mark onto the pier wall (Figure 10). Find the high point of the end drum with a level and measure the OFFSET from the high point to the projection device. It is imperative that the OFFSET DISTANCE be the same (within 1/8 in.) on both ends. It is also desirable to have the projection device positioned in the same place for subsequent inspections. Record the HEIGHT the projection device stands above the end drum skin plate. Again it is imperative that the HEIGHT OFF the GATE is the same (within 1/16-in.) on both ends. It is also desirable to keep the HEIGHT the same for subsequent inspections. Raise the gate to the 6-ft open position (Figure 11). Project another mark on the pier wall. At 6-ft open, the projection device should be downstream of the high point of the gate. Best results are obtained if the device is approximately 2-ft circumferentially from high point with the gate at 6-ft open. Next record the DISTANCE BETWEEN the 6-ft OPEN AND the CLOSED MARKS on both ends of the gate (Figure 12). Measurements should be made to the nearest 1/16 in.

U.S. ARMY CORPS OF ENGINEERS
ROLLER DAM GATE STRUCTURE INSPECTION

PAGES 4, 5, and 6 COMPLETED UNDER
(1) BULKHEADED OR (2)OUT OF OPERATION CONDITIONS
(WITH GATE LIFTED OUT OF WATER): (no.)___

INSPECTION DATE: _____ INSPECTED BY: _____
CURRENT UPPER POOL ELEVATION: (ft) _____
CURRENT LOWER POOL ELEVATION: (ft) _____

RACK ANCHORAGE DETERIORATION

	DRIVEN END	NON-DR.END
CONCRETE CRACKED OR SPALLED?	Y N	Y N
IS THERE EVIDENCE OF MOVEMENT?	Y N	Y N

RACK CONNECTIONS DETERIORATION

NUMBER OF BOLTS/NUTS:	DRIVEN END	NON-DR.END
CORRODED?	_____	_____
LOOSE?	_____	_____
MISSING?	_____	_____

RIM CONNECTIONS DETERIORATION

NUMBER OF BOLTS/NUTS/RIVETS:	DRIVEN END	NON-DR.END
CORRODED?	_____	_____
LOOSE?	_____	_____
MISSING?	_____	_____

RIM/RACK TOOTH DAMAGE
TYPE OF DAMAGE: CHIPPED (H), DEFORMED (D), PITTED (P), GOUGED (G), EXCESSIVE WEAR (W)

RIM TOOTH NUMBER	DAMAGE TYPE	%SURFACE AREA	RACK TOOTH NUMBER	DAMAGE TYPE	%SURFACE AREA
DRIVEN END					
_____	(H,D,P,G,W)	_____	_____	(H,D,P,G,W)	_____
NON-DRIVEN END					
_____	(H,D,P,G,W)	_____	_____	(H,D,P,G,W)	_____

RIM/RACK TRACK DAMAGE

IS THERE DEFORMATION OF THE

	DRIVEN END	NON-DR.END
RIM TRACK?	Y N	Y N
RACK TRACK?	Y N	Y N

GUARD RAIL DAMAGE

	DRIVEN END	NON-DR.END
IS THE GUARD RAIL DEFORMED?	Y N	Y N
IS DEFORMATION GREATER THAN 1-in.?	Y N	Y N

Page 4 Comments: Field data

Completed at-site inspection UNDER BULKHEADED OR OUT OF OPERATION CONDITIONS.

Record the INSPECTION DATE, name of inspector(s), and the CURRENT UPPER and LOWER POOL ELEVATIONS relative to mean sea level.

RACK ANCHORAGE DETERIORATION: Indicate the presence of excessive CRACKED OR SPALLED CONCRETE along the length of the rack anchorage. Excessive concrete spalling may indicate a displacement occurred at this location at some time and may or may not show up in the current inspection. Small hairline cracks, probably caused by thermal expansion or contraction of the concrete, should be ignored in this analysis. Indicate if THERE IS EVIDENCE OF relative MOVEMENT between the pier and rack.
RACK CONNECTIONS DETERIORATION: Observe the BOLTS and NUTS used to connect the segments of the rack together and to connect the rack to the anchorage. Record the number of connection BOLTS/NUTS that are significantly CORRODED. Significant corrosion means an approximate 10% volume reduction. Also record the number of NUTS that are LOOSE. This is done with a torque wrench or by visual inspection for signs of movement between the bolted components during operation. Record the number of connection BOLTS/NUTS that are broken or MISSING.

RIM CONNECTIONS DETERIORATION: Observe the BOLTS, NUTS and/or RIVETS used to connect the segments of the rim together and to the load disc. Indicate the number that are CORRODED, LOOSE, and/or MISSING.

RIM/RACK TOOTH DAMAGE: Record the predominate type of damage to the RIM or the RACK teeth (CHIPPED, DEFORMED, PITTED, GOUGED, EXCESSIVE WEAR select one) on the worst tooth. CHIPPED teeth have small pieces broken off. DEFORMED teeth appear bent. PITTED teeth have minor loss of steel in localized areas due to interaction with the environment. GOUGED teeth have groves or holes due to interference by debris. WEAR is a decrease in the thickness of the tooth (Figure 13). If the rim and/or rack teeth appear to have lost 10% or more thickness on any portion of the tooth surface then there is EXCESSIVE TOOTH WEAR. Also record an estimated PERCENT of SURFACE AREA that has the damage. Identify the tooth with a TOOTH NUMBER using the following convention: rack tooth 1 is the highest, rim tooth 1 would come to rest on rack tooth 1 if the gate were rolled all the way up (Figure 14). It may be helpful to use construction drawings and the segmentation of the rim to determine the rim tooth number.

RIM/RACK TRACK DAMAGE: Select the worst 1-ft length of track and observe whether there is any damage (flattening, loss of steel) that changes the rim/rack contact area by 10% or more.

GUARD RAIL DAMAGE: If DEFORMATION in any direction exists, answer Yes to the first question. If damage is GREATER THAN 1 in., indicate by answering Yes to the second question.

ROLLER DAM GATE STRUCTURE INSPECTION

SEAL DAMAGE

IS LEAKAGE CONTROL CRITICAL? Y N

DAMAGED (D) AND MISSING (M) SECTIONS OF SEALS.
LOCATION: BOTTOM (B), DRIVEN (D), NON-DRIVEN (N)

	COND'N(D,M)	LOC'N(B,D,N)	LENGTH(in.)	DIST UPSTM TOP/D.E.(ft)
(1):				
(2):				
(3):				

END SHIELD DAMAGE

	DRIVEN END	NON-DR. END
NUMBER OF LOOSE OR MISSING BOLTS?		
SECTIONS OF END SHIELD DAMAGE/MISSING?	Y N	Y N

CRACKS
COMPONENTS: DRUM SKIN PLATE (D), DOWNSTREAM CENTER 1/3 OF DRUM (C), END DISC (E), CHAIN ANCHOR (H), UPPER APRON (U), LOWER APRON (A), END SHIELD (S)

	COMPONENT	LENGTH (in.)	LOCATION
(1):			
(2):			
(3):			

COMPLETE IF INTERIOR OF GATE IS ACCESSED
COMPONENTS: PURLINS (P), INTERNAL TRUSSES (T), LOAD DISC (L)

	COMPONENT	LENGTH (in.)	LOCATION
(1):			
(2):			
(3):			

DENTS
COMPONENTS: DRUM SKIN PLATE (D), UPPER APRON (U), LOWER APRON (A), END DISC (E), END SHIELD (S)

	COMPONENT	HEIGHT(ft)	WIDTH(ft)	DEPTH(in.)	LOCATION
(1):					
(2):					
(3):					

COMPLETE IF INTERIOR OF GATE IS ACCESSED
COMPONENTS: PURLINS (P), INTERNAL TRUSSES (T), LOAD DISC (L)

	COMPONENT	LENGTH OF DENT (in.)	OUT OF PLANE DISTANCE(in.)	LOCATION
(1):				
(2):				
(3):				

Page 5 Comments: Field data

Completed at-site inspection UNDER BULKHEADED or OUT-OF-OPERATION CONDITIONS.

SEAL DAMAGE: LEAKAGE CONTROL may be considered CRITICAL at certain sites that generate electrical power. Record any DAMAGED (D) or MISSING (M) SECTIONS OF SEAL and record the general LOCATION (LOC'N) as, BOTTOM (B), DRIVEN (D), or NON-DRIVEN (N). A section of seal is considered damaged if it is cracked, ripped, or loose. Missing sections refer to complete sections broken off because of debris, age, or other causes. The LENGTH of the damage to the seal should be recorded. The specific location is recorded when the gate is in the closed position as the DISTANCE from the UPSTREAM TOP corner of the end shield for side seals. In the case of a damaged bottom seal, record the distance from the DRIVEN END of the gate.

END SHIELD DAMAGE: Record the number of LOOSE OR MISSING end shield BOLTS used to connect the end shield to the gate or to fasten the side seals to the end shield. Indicate if there are any SECTIONS OF the END SHIELD that are DAMAGED or MISSING.

CRACKS: List requested information for any COMPONENTS with cracks. Specifically record the LENGTH, and LOCATION of any cracks on the DRUM SKIN PLATE, a transverse crack in the DOWNSTREAM CENTER 1/3 of the DRUM, END DISC, CHAIN ANCHOR, UPPER APRON, LOWER APRON, and END SHIELD. All measurements are made with a ruler or tape measure. Record the LOCATION of cracks in the skin plate as the distance from the driven end of the gate. Record the location of any cracks as driven end or non-driven end if they are on the end disc or end shield. For cracks in the drum, record the circumferential distance to the crack. Use the following convention (Figure 15): when the gate is in the closed position, approximate the circumferential distance from the highest point of the skin plate to the crack. Revolve the tape measure about the gate and into the lower pool first. For a crack in the chain anchor, record the radial distance out from the end drum skin plate. For cracks in the aprons, record the distance from the driven end of the gate. Also record the distance from the point where apron and drum skin plates are in contact (Figure 15).

IF the INTERIOR OF the GATE IS ACCESSED, any cracks in the PURLINS, INTERNAL TRUSSES, or LOAD DISC should be measured and recorded. Use construction drawings to determine the number of the purlin with the crack. Also record which trusses the purlin crack is between. Number the internal trusses either according to construction drawings or from the driven end. Record the number of the internal truss with crack(s). Record driven or non-driven for any load disc cracks. Also record the number of the nearest purlin.

ROLLER DAM GATE STRUCTURE INSPECTION

SEAL DAMAGE

IS LEAKAGE CONTROL CRITICAL? Y N

DAMAGED (D) AND MISSING (M) SECTIONS OF SEALS.
LOCATION: BOTTOM (B), DRIVEN (D), NON-DRIVEN (N)

	COND'N(D,M)	LOC'N(B,D,N)	LENGTH(in.)	DIST UPSTM TOP/D.E.(ft)
(1):				
(2):				
(3):				

END SHIELD DAMAGE

	DRIVEN END	NON-DR. END
NUMBER OF LOOSE OR MISSING BOLTS?		
SECTIONS OF END SHIELD DAMAGE/MISSING?	Y N	Y N

CRACKS
COMPONENTS: DRUM SKIN PLATE (D), DOWNSTREAM CENTER 1/3 OF DRUM (C), END DISC (E), CHAIN ANCHOR (H), UPPER APRON (U), LOWER APRON (A), END SHIELD (S)

	COMPONENT	LENGTH (in.)	LOCATION
(1):			
(2):			
(3):			

COMPLETE IF INTERIOR OF GATE IS ACCESSED
COMPONENTS: PURLINS (P), INTERNAL TRUSSES (T), LOAD DISC (L)

	COMPONENT	LENGTH (in.)	LOCATION
(1):			
(2):			
(3):			

DENTS
COMPONENTS: DRUM SKIN PLATE (D), UPPER APRON (U), LOWER APRON (A), END DISC (E), END SHIELD (S)

	COMPONENT	HEIGHT(ft)	WIDTH(ft)	DEPTH(in.)	LOCATION
(1):					
(2):					
(3):					

COMPLETE IF INTERIOR OF GATE IS ACCESSED
COMPONENTS: PURLINS (P), INTERNAL TRUSSES (T), LOAD DISC (L)

	COMPONENT	LENGTH OF DENT (in.)	OUT OF PLANE DISTANCE(in.)	LOCATION
(1):				
(2):				
(3):				

Page 5 Comments (continued): Field data

Completed at site inspection UNDER BULKHEADED OR OUT OF OPERATION CONDITIONS.

DENTS: Record any observed DENTS in the DRUM SKIN PLATE. Any dents in the UPPER or LOWER APRONS should also be recorded. The HEIGHT, WIDTH, and DEPTH of dents are measured using a ruler or tape measure. Record the LOCATION as the distance from the driven end of the gate and the circumferential distance using the convention described under CRACKS. In the case of a dent in an END DISC or END SHIELD, record whether it is on the driven or non-driven end.

IF the INTERIOR OF the GATE IS ACCESSED, dents in PURLINS, INTERNAL TRUSSES, and LOAD DISCS should be recorded. The LENGTH, OUT OF PLANE DISTANCE, and LOCATION of each dent is recorded. The out of plane distance refers to the displacement of the member with respect to its original longitudinal axis. The location of purlin dents are recorded as the purlin number and the numbers of the two trusses on either side of the dented purlin. If a dent is in an internal truss, the number of the internal truss with the dent is recorded. For load disc dents, record which disc and the number of the nearest purlin.

ROLLER DAM GATE STRUCTURE INSPECTION

CORROSION (C) or EROSION (E)

COMPONENTS	C OR E	SECT THICK	MAX DEPTH	AVG DEPTH	% AREA	or NO. PITS	AVG DIA
UPSTM. SPLASH ZONE							
DNSTM. SPLASH ZONE							
OTHER SKIN PLATE							
UPPER APRON							
LOWER APRON							
DRIVEN RIM							
DRIVEN RACK							
DRIVEN END DISC							
DRIVEN END SHLD							
NON-DR. RIM							
NON-DR. RACK							
NON-DR. END DISC							
NON-DR. END SHLD							
CHAIN ANCHOR							
COMPLETE IF INTERIOR ACCESSED							
INTERNAL TRUSSES							
PURLINS							
CONNECTIONS							
DRIVEN LOAD DISC							
NON-DR. LOAD DISC							
CHAIN ANCHOR SEG.							

Page 6 Comments: Field Data

Completed at-site inspection UNDER BULKHEADED OR OUT OF OPERATION CONDITIONS.

CORROSION: A 1-sq-ft area of corrosion or erosion is selected on each COMPONENT (Figure 16) to characterize the maximum density of corrosion or erosion. For each component, indicate if corrosion (C) or erosion (E) caused the material loss. Estimate or check drawings for the original section thickness (SECT THICK) of each component. It is likely that the skin plate thickness varies from one end of the gate to the other. Therefore, record a section thickness that corresponds to the plate thickness in the region with the most severe corrosion. When looking for the region with the most severe corrosion, pay particular attention to the splash zones. The maximum pitting depth (MAX. DEPTH) is recorded in column 3. For the 1 sq ft, the average pitting depth (AVG DEPTH) is also recorded. Deterioration can be measured in one of two ways. For the selected area, record either the percentage of the area (% AREA) that is pitted or count the actual number of representative pits (NO. PITS). If the data was entered by counting the number of pits, record the average diameter (AVG DIA) of the representative pits in the last column. In some cases, when the percentage area method is used and the deterioration is uniform, the percentage of area affected could be 100 percent and the average pitting depth is the average thickness reduction.

ROLLER DAM GATE STRUCTURE INSPECTION

COMPLETED UNDER BULKHEADED CONDITIONS

INSPECTION DATE: _____ INSPECTED BY: _____
CURRENT UPPER POOL ELEVATION: (ft) _____
CURRENT LOWER POOL ELEVATION: (ft) _____

DOWNSTREAM DEFLECTION

	NO HEAD	FULL HEAD
TOP HORIZONTAL RULER (in.)	_____	_____
BOTTOM HORIZONTAL RULER (in.)	_____	_____
VERTICAL RULER (in.)	_____	_____

Page 7 Comments: Field Data

Completed at-site inspection UNDER BULKHEADED CONDITIONS.

Record the INSPECTION DATE, name of inspector(s), and the CURRENT UPPER and LOWER POOL ELEVATIONS relative to mean sea level.

DOWNSTREAM DEFLECTION: Place transit on pier so the center of the gate can be viewed through the eye piece. Level the transit. Fasten two HORIZONTAL RULERS to the middle of the gate separated by approximately 3 ft vertically. Orient the RULERS so that the 12-in. mark is downstream. Also fasten a VERTICAL RULER to the middle of the gate. Orient the VERTICAL RULER so the 12-in. mark is down. The group of rulers must be positioned on the vertical centerline of the drum (Figure 17). To read all three rulers with only one transit, use the following technique. Ensure that the transit cannot rotate from side to side by locking the horizontal rotation of the transit. Keep it locked for the entire procedure. First, read the TOP HORIZONTAL RULER under the NO HEAD condition. Record the reading in the first blank under NO HEAD. Second, rotate transit scope vertically to the lower ruler and then lock it in that position. Record the reading on the BOTTOM HORIZONTAL RULER in the second blank of the NO HEAD measurements. Also read and record (in the third blank under NO HEAD) the measurement on the VERTICAL RULER. Next remove the bulkheading, fully loading the gate. Read the BOTTOM HORIZONTAL and VERTICAL RULERS, and record the readings in the FULL HEAD COLUMN in the second and third blanks. Unlock the transit scope vertically. Rotate the scope to view the TOP HORIZONTAL RULER. Record the reading in the first blank under FULL HEAD.

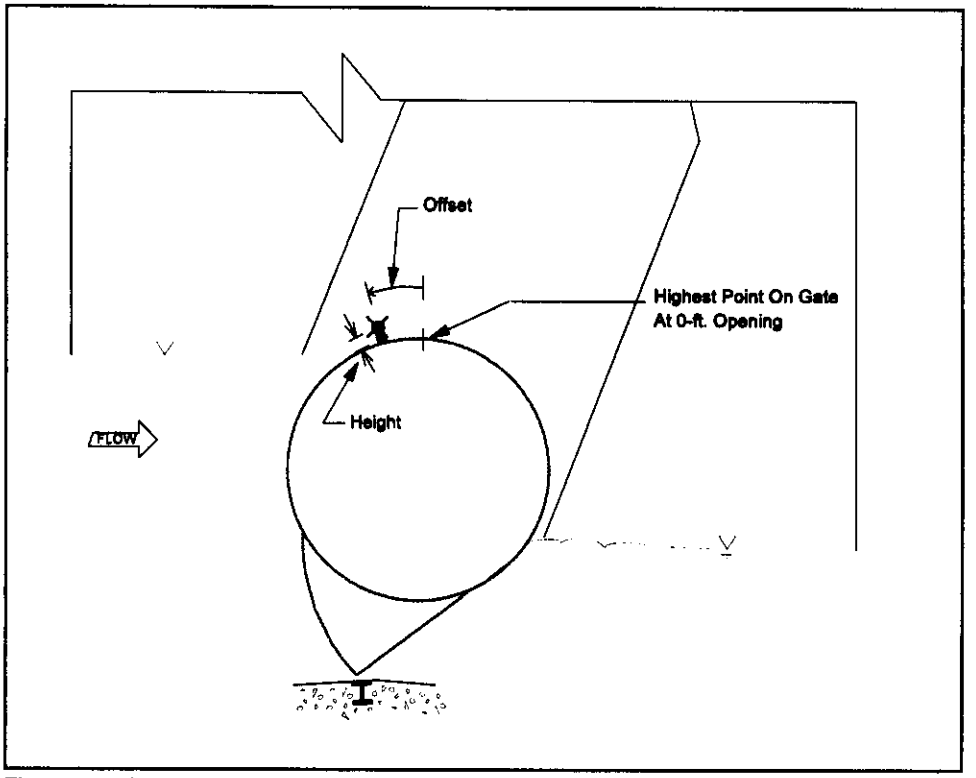

Figure 10. Start point for torsional misalignment measurement

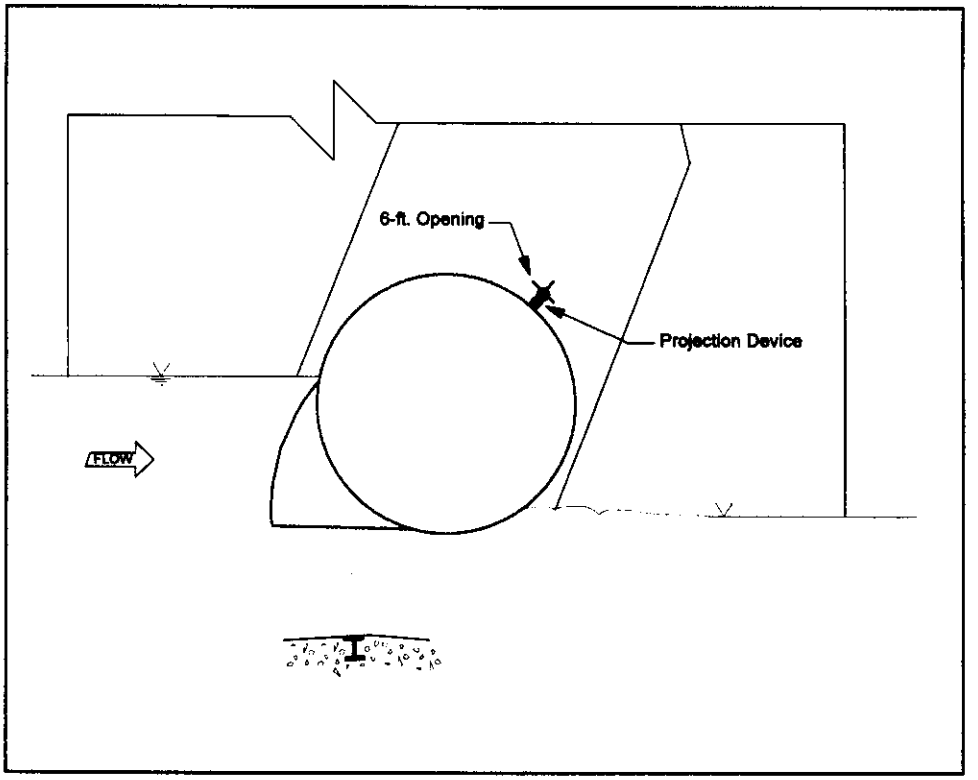

Figure 11. Second point for torsional misalignment

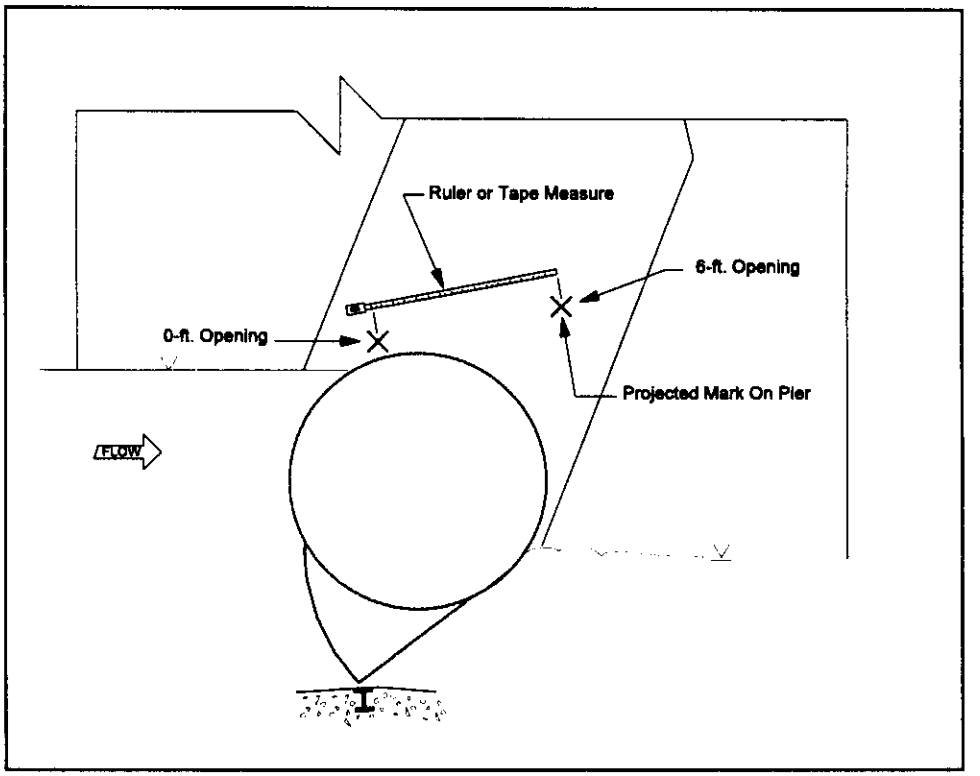

Figure 12. Measurement of torsional misalignment

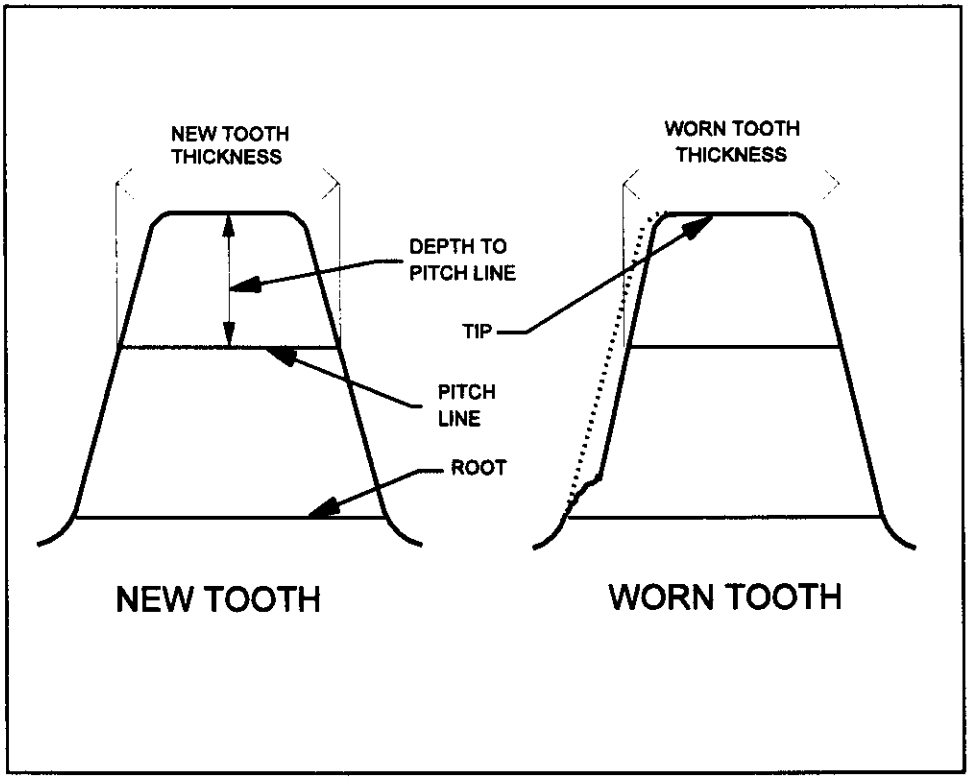

Figure 13. Tooth wear

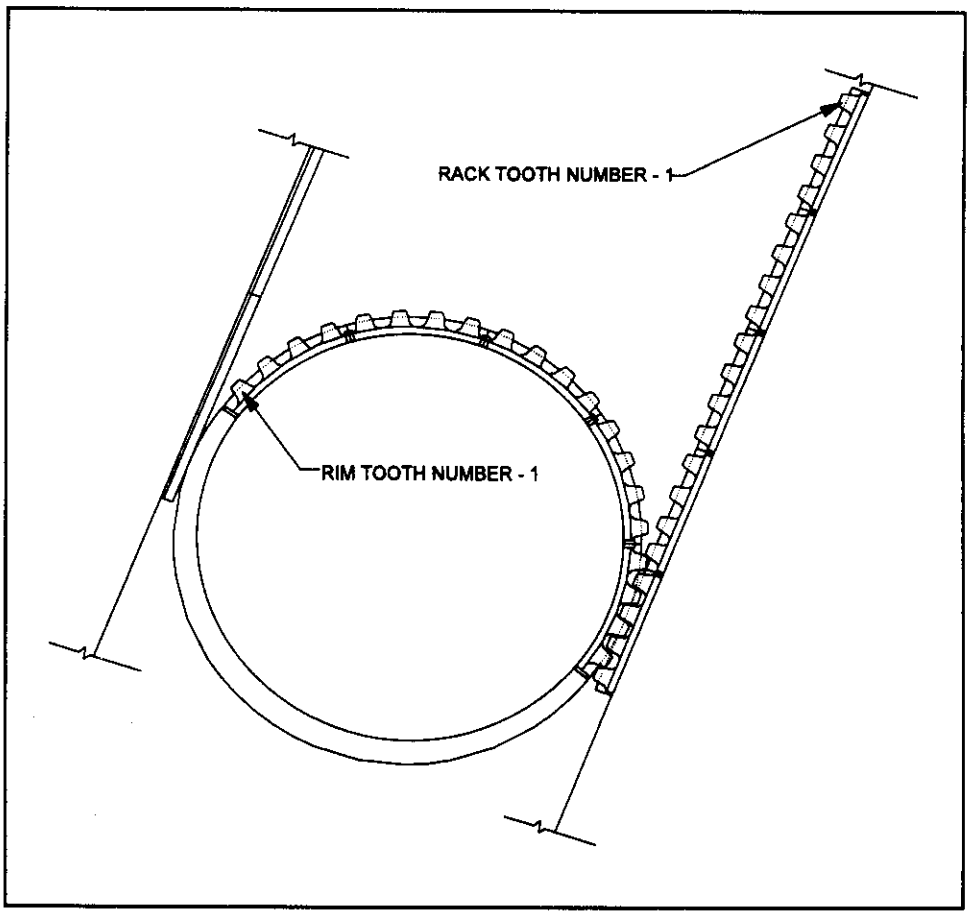

Figure 14. Tooth numbering convention

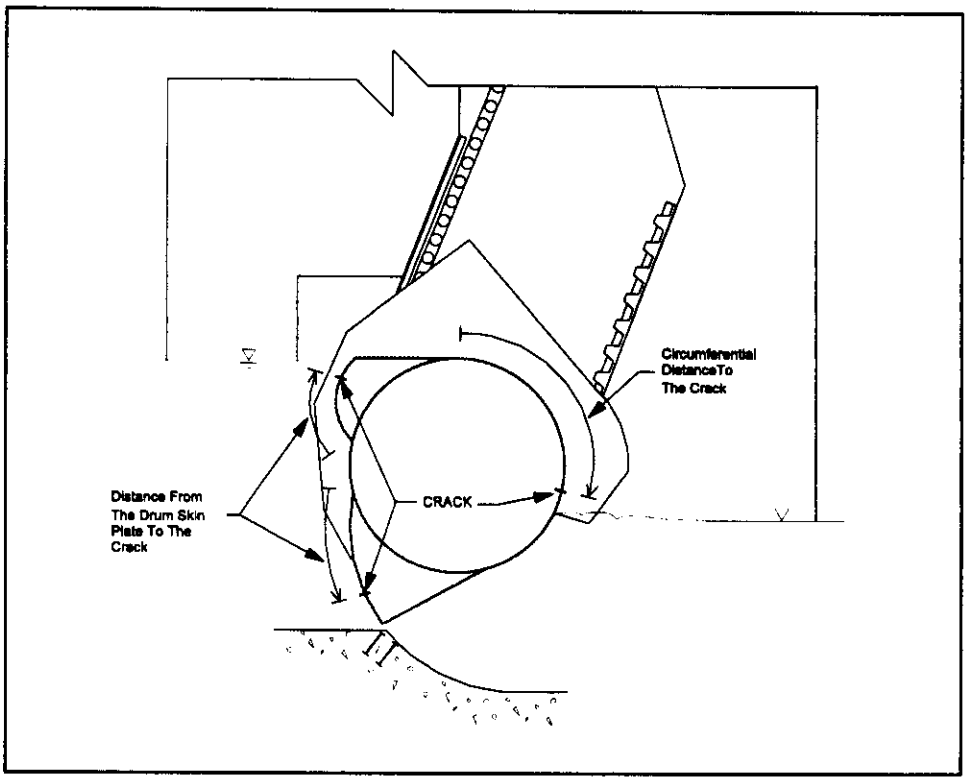

Figure 15. Convention for recording crack locations

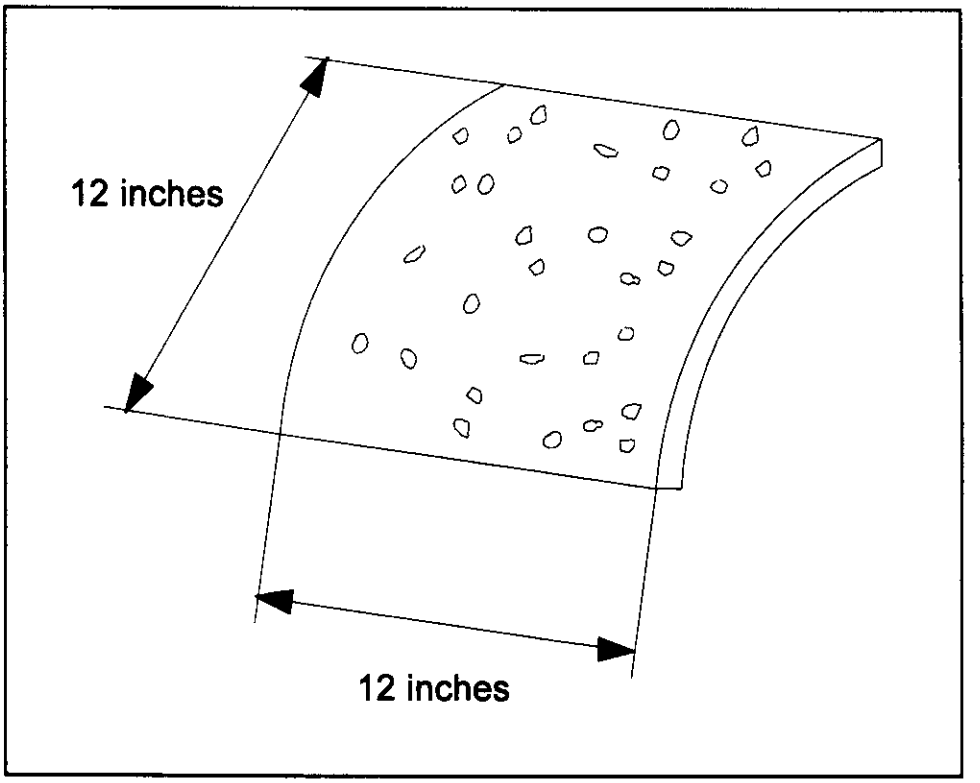

Figure 16. Corrosion measurement

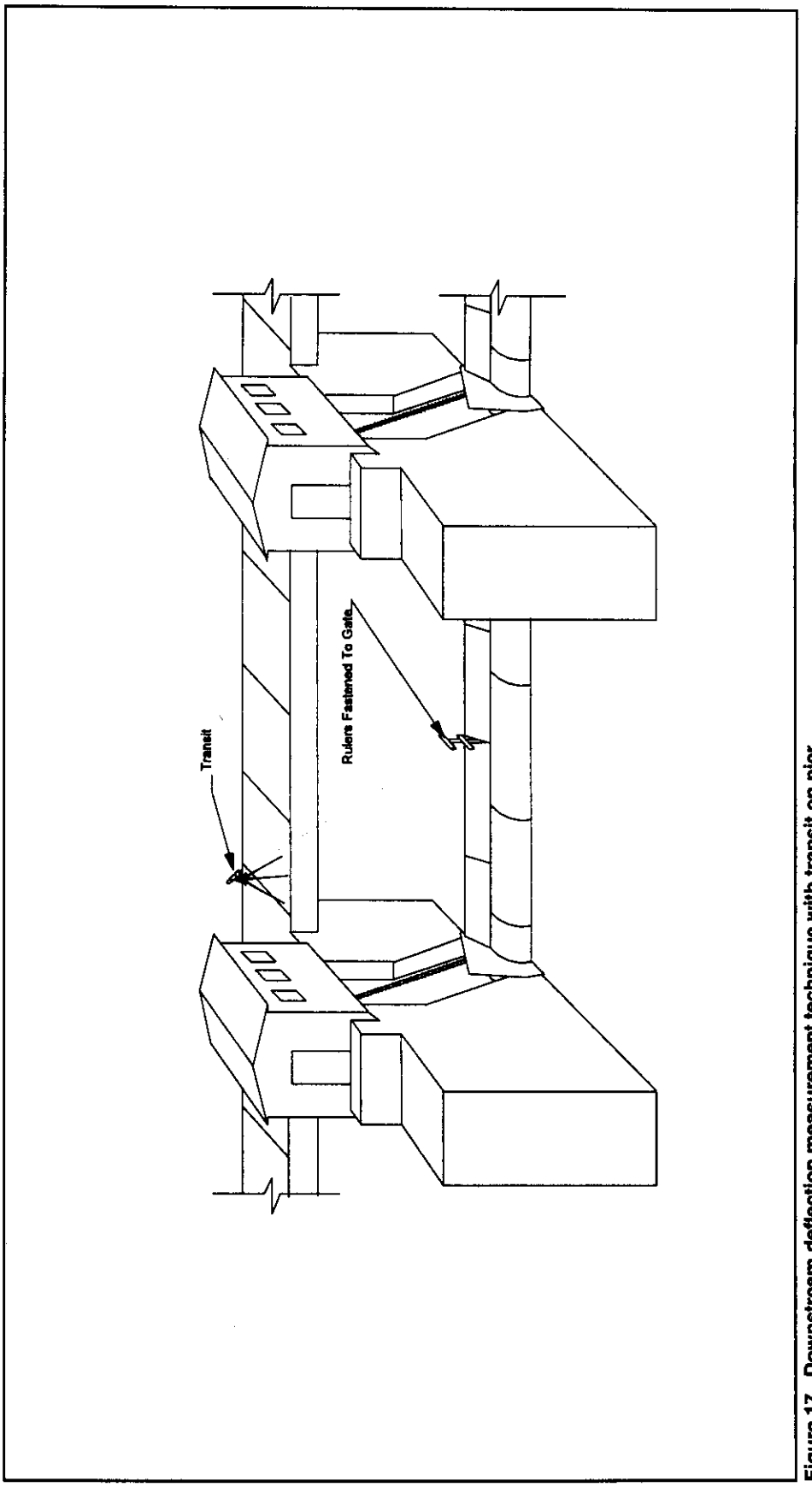

Figure 17. Downstream deflection measurement technique with transit on pier

3 Condition Index

Previously defined in Chapter 1, the CI definition is expanded here. To describe the gate condition quantitatively, specific gate distresses were determined. Rating of the gate CI will depend on the individual distress ratings that rate the safety and serviceability of the roller dam gate. Table 1 lists the 10 roller dam gate distresses and briefly describes each distress. Two distresses are broken into three and four subdistresses. Each distress has one or more qualitative or quantitative measurement that will be made to assess condition. The measurement is used as an X value. During preliminary field visits and meetings, U.S. Army Corps of Engineers experts were asked to determine limiting values of X for each of the distresses. The limiting value is X_{max} and is the value of X that will result in a CI equal to 40. Table 2 shows that a CI of 40 means that the structure needs immediate attention. The quantitative definition of the individual CI is:

$$\textit{Condition Index} = 100(0.4)^{X/X_{max}} \tag{3.1}$$

Figure 18 is a graph of X/X_{max} versus the CI. Depending on the inspection conditions, each of the 10 distresses can be assessed to a greater or lesser degree. For example, for a complete inspection of the rim, the gate must be out of the river. If the gate is left in its normal operating condition, only a partial rim inspection is possible. Table 3 lists the distresses and notes the type of inspection that is possible given inspection conditions of: normal operation, out of operation, or bulkheaded (see **Overview of Inspection Procedure**, Chapter 2). Inspections are divided into three levels of detail: none, partial, or full inspection.

When a roller dam gate is designed and constructed correctly, it has an initial CI of 100. Over time, normal service and environmental factors adversely affect the gate's condition. This deterioration with time will be reflected in a declining CI. In the following sections, each of the 10 distresses are defined and discussed. Possible causes for each of the distresses are listed followed by a discussion of the measurement and a development of the limiting value. Examples are given for each distress to show how measurements of X and X_{max} values are used to obtain a CI.

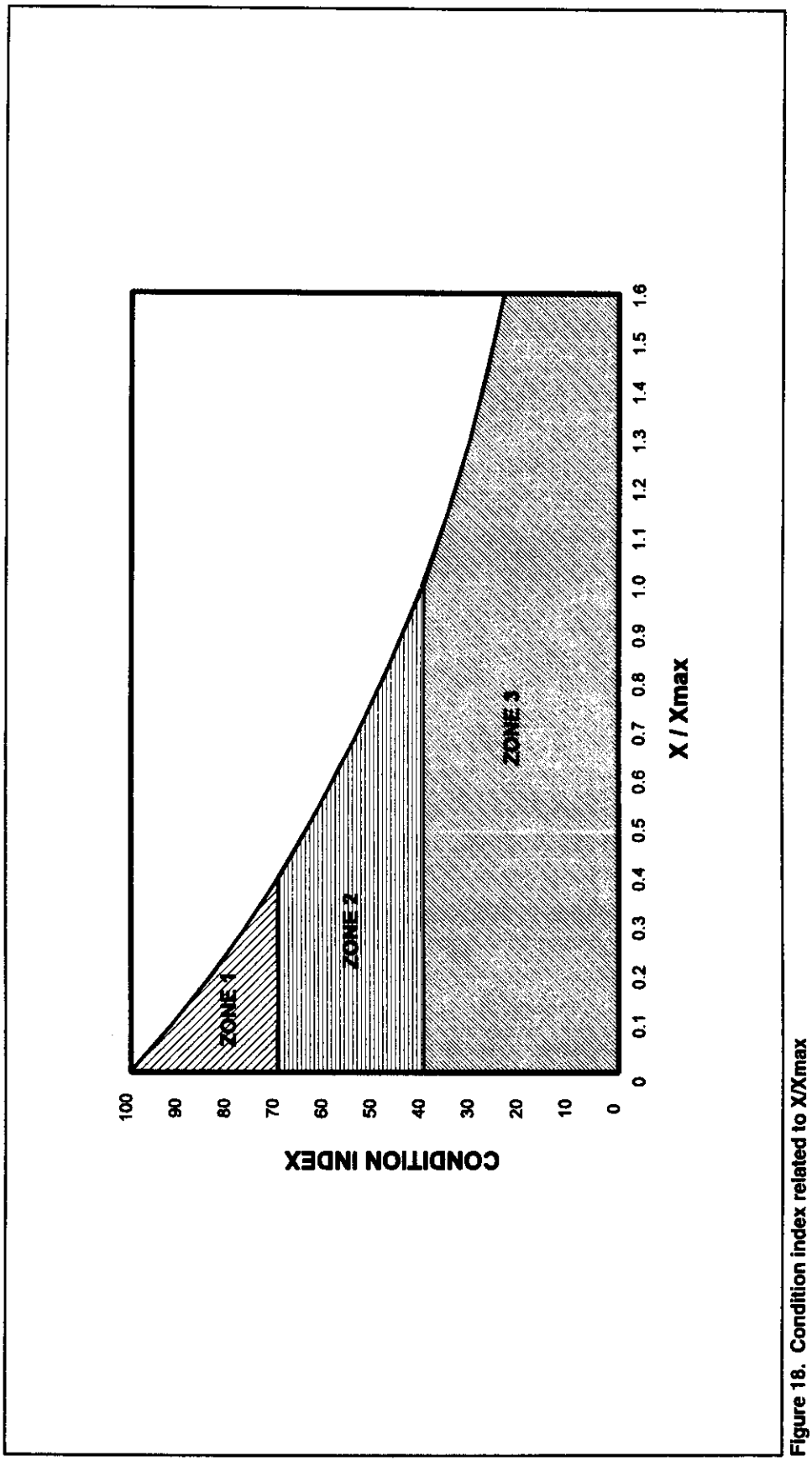

Figure 18. Condition index related to X/Xmax

Noise, Jumping, and Vibration Distress

Definitions and Causes

Noise, jumping, and vibration are abnormal sounds or motions the roller gate makes while being operated. Possible causes for noise, jump, and vibration are:

- debris caught in the rack/rim
- damaged gate
- damaged seals or end shields
- damaged rim or rack teeth.

Measurement and Limits

While the gate is raised and lowered, any noise, jump, or vibration is recorded. If any of the three exist, it should be further classified as normal or abnormal. Normal noise, jumping, or vibration does not reduce the CI. The position of the gate when the noise, jumping, or vibration occurred is also recorded for reference. The possible combinations for noise, jumping, and vibration and the resulting CIs are given below.

Abnormal Noise, Jumping, and Vibration	CI
None	100
Yes for any one of the three	70
Yes for any two of the three	40
Yes for all three	30

Although this distress is more subjective than quantitative, it can be a valuable indicator of potential structural problems. For example abnormal jumping could be an indication of damage to the rim or rack.

Example: As a submersible gate was raised, it made a sudden jump. The jump was recorded as abnormal and occurred at a position of 1-ft open. Also, some noise was heard in the seals as the gate began to be raised, but it was recorded as normal. The CI is 70 since the jumping was abnormal. Table 2 shows that the CI falls in Zone 1 and can be described as Good. If the jump had not occurred, the CI would have been 100 because the noise in the seals initially was considered normal.

Vibration With Flow Distress

Definition and Causes

Vibration with flow is vibration of the gate caused by water flowing over or under the gate. Severe vibration with flow or even moderate vibration over an extended period could cause damage to the gate. Some possible causes for vibration with flow are:

- loose connections
- damaged bottom seal
- damaged apron(s).

Measurement and Limits

Any vibration of the gate caused by flowing water should be recorded. The opening of the gate when the vibration occurred should also be recorded. The CIs for the different levels of gate vibration are:

Level Description	Level	CI
No vibration	0	100
Feel with finger tips on gate or end shields, hear humming noise	1	90
Large ripples on upper pool 1/2-inch height	2	70
Rattles end shields and bracing	3	40
Vibrates or shakes pier	4	30

Often the vibration will not continue if the gate position is adjusted. If adjusting the gate height eliminates any vibration with flow, raise the CI one level.

Example: When a submersible gate was lowered to an opening of -4 ft, it began to vibrate. The gate vibration was sufficient to cause an end shield to shake and rattle. When the gate position was changed, the vibration stopped. The CI for vibration with flow is 70 because level 3 vibration was observed but was eliminated by changing the gate position. Table 2 lists the condition as Good. If vibration would have continued after the position was changed, the CI would have been 40.

Torsional Misalignment Distress

Definition and Causes

Torsional misalignment is excessive twist in the roller gate due to the torsional forces acting on it (Figure 19). Possible causes of torsional misalignment are:

- corrosion of the skin plate
- corrosion of the internal trusses and longitudinal purlins
- corrosion and loosening of connections.

Measurement and Limits

The purpose of the torsional misalignment measurement is to detect relative torsional rotations of the driven and nondriven ends when the gate is opened. Marks are made on the piers on both ends when the gate is in the closed position and again at the 6-ft open position (see Chapter 2). The distances between the two marks made on the driven end and the nondriven end are Z_{drv} and Z_{ndrv}, respectively. The X value uses the field measurements to assess the relative angle change between the two ends:

$$X = \frac{|Z_{drv} - Z_{ndrv}|}{Z_{drv}} \tag{3.2}$$

From geometry equations for the motion of a roller gate when rolled up the rack and a study of roller gate geometry, the limiting value X_{max} was determined by assuming the limiting angle of twist, $\Delta\theta_{max}$, between the two ends of the gate corresponds to a shear strain of 1/3 of the yield strain (see Appendix A for details of this development). It was found that X_{max} depends on two independent variables: The length of the gate L (ft) and the rim radius R (inches). A multiple regression analysis was performed for both single-apron and double-apron gates using a first-order interaction model. The resulting limiting value for gates with one apron is:

$$X_{max} = 0.00201 + (1.86x10^{-4})L - (1.88x10^{-5})R - (1.50x10^{-8})LR \tag{3.3}$$

The resulting limiting value for gates with two aprons is:

$$X_{max} = 0.00233 + (2.19x10^{-4})L - (2.18x10^{-5})R - (1.50x10^{-8})LR \tag{3.4}$$

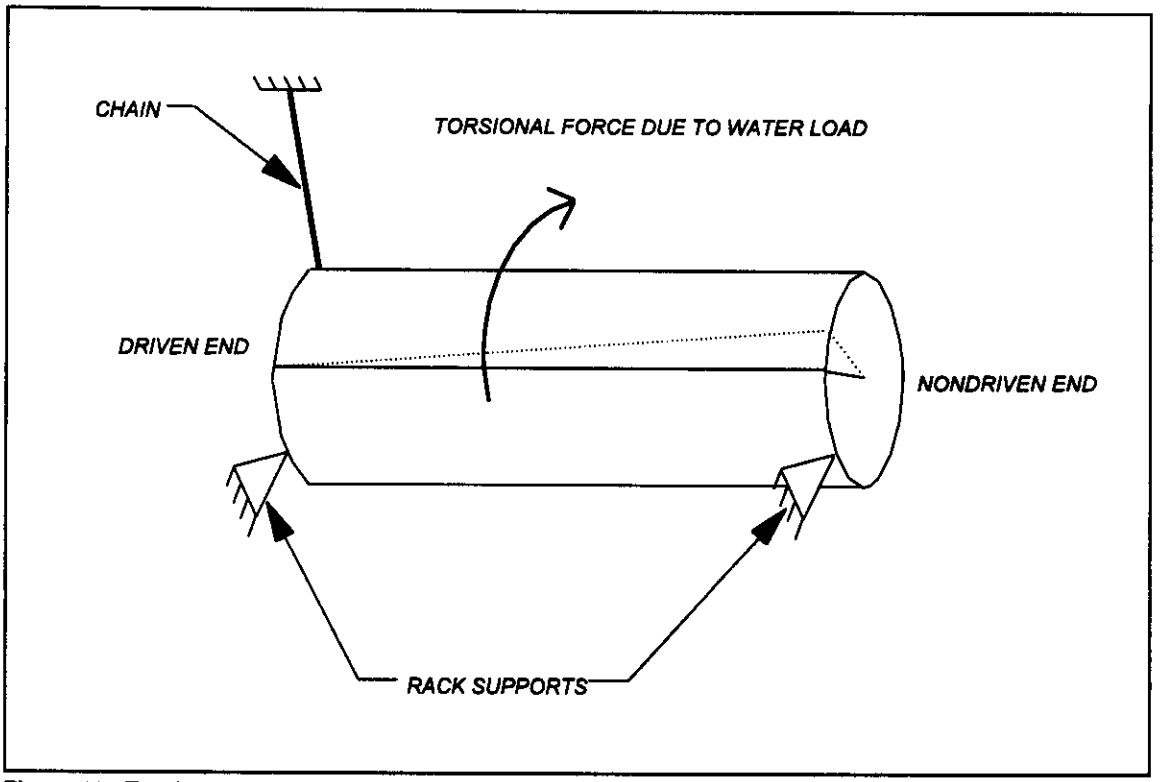

Figure 19. Torsional twist

Table 4 contains torsional misalignment CIs for several gates at three different sites.

Example: A double-apron gate with a length of 100 ft and a rim radius of 88 in. has a torsional misalignment limiting value of $X_{max} = 0.0222$. During an inspection of torsional misalignment, measurements were $Z_{drv} = 49$ in. and $Z_{ndrv} = 48.625$ in. The X value from Equation 3.2 is 0.0077, and the CI = 73 from Equation 3.1. Table 2 describes the gate condition as Good with regard to torsional misalignment.

Table 4. Calculated CIs for torsional misalignment

Lock & Dam	Type	Gate	X	CI
14	Double Apron	5	0.0077	73
14	Double Apron	6	0.0031	88
14	Double Apron	7	0.0037	86
14	Double Apron	8	0.0087	70
21	Double Apron	7	0.0152	53
21	Double Apron	9	0.0162	51
16	Single Apron	7	0.0107	52
16	Single Apron	9	0.0101	54

Rack Deterioration Distress

The rack deterioration distress has four subdistresses:

- Anchorage (Rack Connections) Deterioration (CI_A)
- Rack Tooth Damage (CI_T)
- Rack Track Damage (CI_R)
- Guard Rail Damage (CI_G).

The minimum CI of these four subdistresses is the CI for this distress:

$$CI = Minimum(CI_{A,T,R,G}) \tag{3.5}$$

Anchorage (Rack Connections) Deterioration Subdistress

Definition and Causes

The anchorage deterioration subdistress assesses the condition of the pier concrete near the rack and the rack connection bolts. Possible causes of deterioration of the anchorage are:

- deterioration of the concrete base
- movement of rack relative to pier
- loose connections
- corrosion
- improperly fastened originally.

Measurement and Limits

The driven and nondriven ends are checked for deterioration of the rack connections. The number of visible connection bolts/nuts on each end that are corroded is X_C, and the number of loose or missing bolts/nuts is X_{LM}. The limiting values are:

$$X_{maxC} = 5 \tag{3.6}$$

$$X_{maxLM} = 2 \tag{3.7}$$

The CI for the bolts is the minimum of the CI for the corroded bolts, CI_C , and the loose and missing bolts, CI_{LM}.

$$CI_{BOLTS} = Minimum(CI_C, CI_{LM}) \tag{3.8}$$

The driven and nondriven end piers near the rack are checked for concrete cracks or spalling. Evidence of relative movement between the rack and the pier is noted. A reduction factor of 0.85 is applied to the CI if cracks and spalling are present, and a reduction factor of 0.55 is applied if relative movement is observed. If both conditions are present, both reduction factors are applied.

$$CI = (Reduction\ Factor)(CI_{BOLTS}) \tag{3.9}$$

The CI for the anchorage is:

$$CI_A = Minimum(CI_{drv}, CI_{ndrv}) \tag{3.10}$$

Example: An inspection of the rack anchorage on the driven end of a gate revealed that two corroded bolts were near the water line.

$$X_C = 2$$

No bolts were loose or missing. The CI for the bolts on the driven end is:

$$CI_{bolts} = [100(0.4)^{2/5}] = 69$$

Deep spalling of the concrete along one side of the rack was also present. Therefore, the applicable reduction factor is 0.85.

$$CI_{drv} = 0.85(69) = 59$$

Similar investigation of the nondriven end rack anchorage was also performed. However, no corroded, loose, or missing bolts were observed. The concrete surrounding the rack anchorage was not cracked or spalled. Therefore, the CI for the nondriven end is:

$$CI_{ndrv} = 100$$

The CI for the rack anchorage subdistress is determined by Equation 3.10, and is:

$$CI_A = Minimum(59, 100) = 59$$

The CI of the anchorage falls in Zone 2, and Table 2 describes it as Fair.

Rack Tooth Damage Subdistress

Definition and Causes

The tooth damage distress is an assessment of the damage to the rack teeth. Such damage is classified as chipped, deformed, pitted, gouged, or worn. Possible causes of these types of damage are:

- debris
- damage during construction
- corrosion and interaction with the environment
- misalignment of teeth
- repeated use
- extended periods of gate vibration with flow.

Measurement and Limits

The percent of surface area, X, of the worst tooth on the rack with chipped, deformed, pitted, gouged, and worn teeth is recorded. The limiting value for chipped or deformed is:

$$X_{max} = 20\% \tag{3.11}$$

The limiting value for pitted, gouged, excessive wear is:

$$X_{max} = 40\% \tag{3.12}$$

The CI for rack tooth damage is:

$$CI_T = Minimum(CI_{drv}, CI_{ndrv}) \tag{3.13}$$

Example: The driven end rack teeth of a gate were inspected and several of the teeth had pitting that covered more than 10 percent of the tooth surface area. The worst tooth was selected, and the percent of tooth surface area with the pitting was estimated to be:

$$X_{pitted} = 15\%$$

$$CI_{drv} = [100(0.4)^{15/40}] = 71$$

The nondriven end did not have any tooth damage so the condition index is:

$$CI_{ndrv} = 100$$

The CI for the tooth damage subdistress is determined by Equation 3.13 and in this example is:

$$CI_T = Minimum(71, 100) = 71$$

Table 2 describes the condition as Good.

Rack Track Damage Subdistress

Definition and Causes

Rack track damage is deformation or wear that changes the contact area at the rack track from the original. The change can be either an increase due to flattening out of the track or a decrease due to deformation or loss of steel. Possible causes of damage to the rack track are:

- debris
- construction damage
- operation while misaligned
- previous chain failure
- operation at same position for extended periods.

Measurement and Limits

Any rack track damage that causes a change in contact surface area in excess of 10 percent in a 1-ft length is recorded. The rack track damage CI is determined by the following scale:

Condition	CI_R
No rack track damage	100
One rack track is damaged	70
Both ends have rack track damage	40

Example: During an inspection, significant rack track damage was observed on the nondriven end but not on the driven end. The CI for the rack track damage subdistress is:

$$CI_R = 70$$

The CI for rack track damage falls into Zone 1 of Table 2 and is described as Good.

Guard Rail Damage Subdistress

Definition and Causes

Guard rail damage is deformation of the guard rail in any direction from its original condition. Some possible causes of damage to the guard rail are:

- construction damage
- operation while misaligned
- previous chain failure.

Measurement and Limits

Guard rail deformation in any direction is observed. The condition index for guard rail damage is found by the following rules:

Condition	CI
No Damage	100
Damage of 1 in.	70
Damage Greater Than 1 in.	40

$$CI_G = Minimum(CI_{drv}, CI_{ndrv}) \quad (3.14)$$

Example: During inspection of a gate, damage to the nondriven end guard rail was observed. At the damaged point, the guard rail was deformed approximately 1 in. from its original position.

$$CI_{ndrv} = 70$$

No damage was observed on the driven end guard rail. The CI for guard rail damage is determined by Equation 3.14 and is:

$$CI_G = Minimum(100,70) = 70$$

The condition of the guard rail damage subdistress is described as Good by Table 2.

From Equation 3.5, the CI of the rack deterioration distress can be determined based on the four subdistresses. In this example, the CI is:

$$CI = Minimum(59,71,70,70) = 59$$

Table 2 describes the condition of the rack as Fair.

Rim Deterioration Distress

The rim deterioration distress has three subdistresses:

- Rim Connections Deterioration (CI_C)
- Rim Tooth Damage (CI_T)
- Rim Track Damage (CI_R).

The minimum CI of these three subdistresses is the value for the CI for this distress.

$$CI = Minimum(CI_{C,T,R}) \quad (3.15)$$

Rim Connections Deterioration Subdistress

Definition and Causes

The rim connections deterioration distress assesses the condition of the rim connection bolts. Possible causes of deterioration of the connections are:

- corrosion
- improper fastening originally
- debris
- gate vibration.

Measurement and Limits

The driven and nondriven ends are checked for deterioration of the rim connections. On each end, the number of visible connection bolts and nuts that are corroded is counted. The number of loose or missing bolts and nuts is also counted. The limiting values are given by Equations 3.6 and 3.7. The CI for the rim bolts is determined by Equation 3.8. The CI for the rim subdistress connections deterioration is:

$$CI_C = Minimum(CI_{drv}, CI_{ndrv}) \tag{3.16}$$

Example: An inspection of the rim connections on the driven end of a gate revealed that one bolt was loose.

$$X_L = 1$$

The CI for the bolts on the driven end is:

$$CI_{bolts} = [100(0.4)^{1/2}] = 63$$

Inspection of the nondriven end rim connections was also performed. However, no corroded, loose, or missing bolts were observed. Therefore, the CI for the nondriven end is:

$$CI_{ndrv} = 100$$

The CI for the rack anchorage subdistress is determined by Equation 3.10, and is:

$$CI_C = Minimum[63, 100] = 63$$

The CI of the anchorage falls in Zone 2, and Table 2 describes it as Fair.

Rim Tooth Damage Subdistress

Definition and Causes

The tooth damage subdistress is an assessment of the damage to the rim teeth. Such damage is classified as chipped, deformed, pitted, gouged, or worn. Possible causes of these types of damage are:

- debris
- damage during construction
- corrosion and interaction with the environment
- misalignment of teeth
- repeated use
- extended periods of gate vibration with flow.

Measurement and Limits

The percent of surface area, X, of the worst tooth on the rack with chipped, deformed, pitted, gouged, and worn teeth is recorded. The limiting values are determined by Equations 3.11 and 3.12. The CI for the rim tooth damage subdistress is calculated using Equation 3.13.

Example: The driven end rim teeth of a gate had no damage, so the CI is:

$$CI_{drv} = 100$$

However, two of the teeth on the nondriven end were chipped to the extent that more than 10 percent of the tooth surface area was missing. The worst tooth was selected, and the percent of tooth surface area chipped was estimated to be:

$$X_{chipped} = 15\%$$

The CI for the nondriven end is:

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

The CI for the tooth damage subdistress is determined by Equation 3.13 and in this example is:

$$CI_T = Minimum(100,50) = 50$$

Table 2 describes the condition as Marginal; that is, moderate deterioration exists, but function is still adequate.

Rim Track Damage Subdistress

Definition and Causes

Rim track damage is deformation or wear that changes the contact area at the rim track, from the original. The change can be either an increase due to flattening out of the track or a decrease due to deformation or loss of steel. Possible causes of damage to the rim track are:

- debris
- construction damage
- operation while misaligned
- previous chain failure
- operation at same position for extended periods.

Measurement and Limits

Any rim track damage that causes a change in contact surface area in excess of 10 percent in a 1-ft length is recorded. The rim track damage CI is determined by the following scale:

Condition	CI_R
No rim track damage	100
One rim track is damaged	70
Both ends have rim track damage	40

Example: During an inspection, significant rim track damage was observed on the nondriven end but not on the driven end. The CI for the rim track damage subdistress is:

$$CI_R = 70$$

The CI for rim track damage falls into Zone 1 of Table 2 and is described as Good.

From Equation 3.15, the CI of the rim deterioration distress can be determined based on the three subdistresses. In this example:

$$CI = Minimum(63,50,70) = 50$$

Table 2 describes the rim condition as Marginal.

Seal and End Shield Damage Distress

Definition and Causes

Seal and end shield damage is any visible damage to either the timber or rubber seals or the steel end shield. Damage would include cracked, ripped, or loose seals. Missing portions of the seals are also included under this distress. Damaged end shields can be corroded, dented, or loosely connected to the gate. Some possible causes of such damage are:

- debris and ice
- aging of the timber or rubber seals
- corrosion of the end shield connections
- improper fastening of seals to the end shield.

Measurement and Limits

The location and length of any damaged or missing portions of side seals is recorded. The number of loose or missing seal and end shield connection bolts are counted, although the information is not used in the CI. Any damaged or missing portions of the end shields are noted. The variable X is the measured length of damaged side and bottom seals.

$$X = X_{drv} + X_{ndrv} + X_{bottom} \tag{3.17}$$

If leakage control is not considered critical (i.e., at a nonpower plant location), then the limiting value for seal damage is:

$$X_{max} = (0.20)(L) \tag{3.18}$$

where L is the length of the gate (inches). If leakage control is considred critical, the limiting value for seal damage is:

$$X_{max} = (0.04)(L) \tag{3.19}$$

If portions of the end shield on one end are damaged or missing, the CI is reduced by a factor of 0.85. If the end shields on both ends have damaged or missing portions, the CI is reduced by a factor of 0.70. The CI for seals and end shield damage is determined by multiplying the reduction factor for end shield damage and Equation 3.1.

$$CI = (Reduction\ Factor)(CI_{SEALS}) \tag{3.20}$$

Example: Damage to the driven and nondriven end side seals was observed on a submersible gate 80 ft in length. Leakage control is not considered critical at the site. The length of damage to the side seals was 12 in. on the driven end and 18 in. on the nondriven end:

$$X = 12\,in. + 18\,in. + 36\,in. = 66\,in.$$

A crack in the nondriven end shield was also observed; therefore, the reduction factor of 0.85 is applicable. Since leakage control is not critical, Equation 3.18 is used to determine the limiting value of seal damage.

$$X_{max} = (0.20)(80\text{-}ft)(12\text{-}in./ft) = 192\,in.$$

The CI for the seals is:

$$CI = (0.85)[100(0.4)^{66/192}] = 62$$

Table 2 describes the condition of the seals as Fair.

Cracks Distress

Definition and Causes

Cracks are narrow openings, breaks, or discontinuities in the structural steel that may cause separation of components. Cracks can be caused by:

- fatigue
- brittle fracture
- overstressing of components.

Measurement and Limits

The length and location of any cracks are recorded. The limiting value for the number of cracks in visible exterior components such as drum skin plate (D), end disc (E), and lower apron (A) is:

$$X_{\max D,E,A} = 1 \tag{3.21}$$

For the upper apron (U), end shield (S), purlins (P), and internal trusses (T), the limiting value for the number of cracks is:

$$X_{\max U,S,P,T} = 3 \tag{3.22}$$

If a transverse crack is observed anywhere on the downstream center 1/3 of the drum skin plate (C), or on the chain anchor (H), or load disc (L) then:

$$CI_{C,H,L} = 30 \tag{3.23}$$

Due to the severity of a crack in one of these locations, the crack distress CI becomes 30, and the combined CI for the entire gate also becomes 30.

$$Combined\ CI = 30 \tag{3.24}$$

Otherwise, the CI for cracks is the minimum of the CIs for all these components.

$$CI = Minimum(CI_{D,E,A,U,S,P,T,C,H,L}) \tag{3.25}$$

Example: During an inspection several cracks were counted on a gate. The lower apron had one crack:

$$X_A = 1$$

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

A crack was also found on an end shield:

$$X_S = 1$$

$$CI_S = [100(0.4)^{1/3}] = 74$$

A crack in the chain anchor was also observed:

$$CI_H = 30$$

No other cracks were observed; therefore, the crack CIs for the other components are 100. The overall CI for cracks is determined by Equation 3.25:

$$CI = Minimum(100,100,40,100,74,100,100,100,30,100) = 30$$

The crack distress CI is described as Poor by Table 2. Because the chain anchor is a critical component, the combined CI for the gate automatically reduces to:

$$Combined\ CI = 30$$

Table 2 describes the combined CI as Poor; that is, function is inadequate.

Dents Distress

Definition and Causes

Dents are disfigurations or point deformations of the gate components such as the skin plate. Dents can be a serious structural problem if they significantly reduce the capacity of particular components. Causes include:

- vessel or barge impact
- debris impact
- ice build up between the gate and pier.

Measurement and Limits

The size and location of all dents are recorded. The limiting values for drum skin plate (D), end disc (E), upper apron (U), and lower apron (A), and end shields (S) are:

$$X_{\max D,U,A,E,S} = 10 \tag{3.26}$$

If the interior of the gate is accessed, the limiting values for dents in purlins (P), internal trusses (T), and load discs (L) are:

$$X_{\max P,T} = 3 \tag{3.27}$$

$$X_{\max L} = 1 \tag{3.28}$$

The CI for dents is the minimum of the CIs for all these components:

$$CI = Minimum(CI_{D,U,A,E,S,P,T,L}) \tag{3.29}$$

Example: During an inspection, three dents were observed in the drum skin plate.

$$X_D = 3$$

The limiting value for dents in the drum skin plate is determined by Equation 3.26. The CIs for dents in other components are each 100, because no dents were observed.

$$CI_D = [100(0._)^{3/10}] = 76$$

The CI for dents in the gate is:

$$CI = Minimum(76,100,100,100,100,100,100,100,100,100) = 76$$

The condition of the gate with regard to dents is described as Good by Table 2, indicating only minor deterioration is present.

Corrosion, Erosion Distress

Definition and Causes

Corrosion is a uniform loss of section thickness due to chemical interaction with the environment. Pitting is a localized form of corrosion. Erosion is a loss of section thickness due to a mechanical type of interaction with the environment. Some causes of corrosion and erosion are:

- chemistry of the water versus the gate
- anodic/cathodic reaction between dissimilar metals
- high velocity of water flowing over/under the gate.

Measurement and Limits

The X value is the percentage of section thickness lost in the worst square foot of gate surface. If the percentage of area and the average depth of corrosion is estimated, then:

$$X = \frac{(P)(D)}{T} \qquad (3.30)$$

where P is the percentage of the 1 sq ft that is corroded or pitted, D is the average depth of the corrosion or pits, and T is the steel plate thickness. If the number of pits in the 1 sq ft, N, and the average diameter, d, of the pits is recorded then:

$$X = \frac{(N)\pi(d^2)(D)}{(4)(144)(T)}\ (100\%) \tag{3.31}$$

For drum skin plate (D), upper apron (U), lower apron (A), end disc (E), and end shields (S), the limiting value is:

$$X_{max} = 20\% \tag{3.32}$$

For rims (I), racks (R), chain anchor (H), internal trusses (T), purlins (P), connections (O), load discs (L), and chain anchor segment (G), the limiting value is:

$$X_{max} = 10\% \tag{3.33}$$

The CI for corrosion is the minimum value for the CI of the members.

$$CI = Minimum(CI_{D,U,A,I,R,E,S,H,T,P,O,L,G}) \tag{3.34}$$

Example: Corrosion was observed on the center of a gate drum skin plate. The worst square foot of the pitting was selected and an estimate was made of the percentage of the surface area that was pitted. Inspectors estimated that 30 percent of the area was covered with pitting having an average depth 1/8 in. The thickness of the drum skin plate in that location is 11/16 in. Using Equation 3.30 gives a percentage of volume lost due to the pitting:

$$X = \frac{(30\%)(0.125)}{(0.6875)} = 5.5\%$$

The limiting value given by Equation 3.32 is:

$$X_{max} = 20\%$$

The CI for the drum skin plate is:

$$CI_D = [100(0.4)^{5.5/20}] = 78$$

Table 2 describes the CI as Good.

Example: Corrosion was observed on the center of a gate drum skin plate. The worst square foot of the pitted surface was selected and the number of pits was counted. The 220 pits had an average diameter of 1/2 in. and an average depth of 1/8 in. The thickness of the drum skin plate in that location was 11/16 in. Using Equation 3.31 gives a percentage of volume lost due to the pitting:

$$X = \frac{(220)\Pi(0.5^2)(0.125)}{(4)(144)(0.6875)} = 5.5\%$$

The limiting value given by Equation 3.32 is:

$$X_{max} = 20\%$$

The CI for the drum skin plate is:

$$CI_D = [100(0.4)^{5.5/20}] = 78$$

Table 2 describes the CI as Good. The CI for corrosion is determined by Equation 3.34. In this case, no other corrosion was observed so the CIs for corrosion of the other components are 100. Therefore, the CI is:

$$CI = Minimum(78,100,100,\ldots,100) = 78$$

Table 2 describes the corrosion CI as Good.

Downstream Deflection Distress

Definition and Causes

Downstream deflection is an excessive bending of the gate in the downstream direction. Possible causes for this type of displacement are:

- damage or corrosion of the skin plate, internal trusses, longitudinal purlins, or connections
- overload of the gate during flooding.

Measurement and Limits

Downstream deflection is measured under bulkheaded conditions with the gate in the closed position. The downstream deflection measured on the bottom horizontal ruler in the current inspection is δ. The X value is δ multiplied by a factor for head conditions (see Figure 20). The current measurement is modified to estimate the horizontal downstream deflection that would be measured if the pool elevations would have matched the design values found on the drawings.

$$X = \delta \left(\frac{H_{Adesign}^2 - H_{Bdesign}^2}{H_A^2 - H_B^2} \right) \tag{3.35}$$

where H_A is the upper pool elevation minus the sill elevation (ft) and H_B is the lower pool elevation minus the sill elevation (ft) (see Figure 21). The parameters $H_{Adesign}$ and $H_{Bdesign}$ are the design upper pool elevation minus the sill elevation and the design lower pool elevation minus the sill elevation, respectively. The gate is assumed to act as a simply supported beam with a uniform load. The limiting value, X_{max}, is equal to a deflection that will cause a strain due to flexure of 1/2 of the yield strain when design head conditions exist.

$$X_{max} = (5.93x10^{-5})\frac{L^2}{r_d} \tag{3.36}$$

where L is the length of the gate in inches and r_d is the radius of the drum in inches. For a more detailed development of the limiting value, X_{max}, see Appendix B.

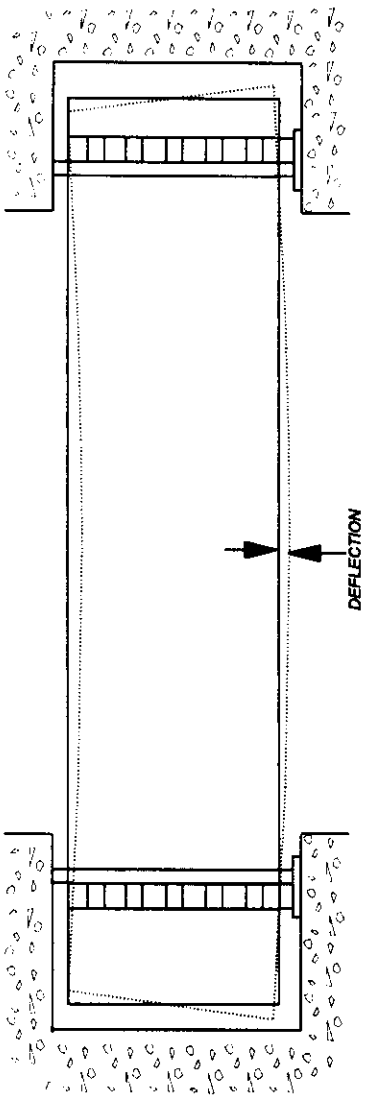

Figure 20. Deflected shape

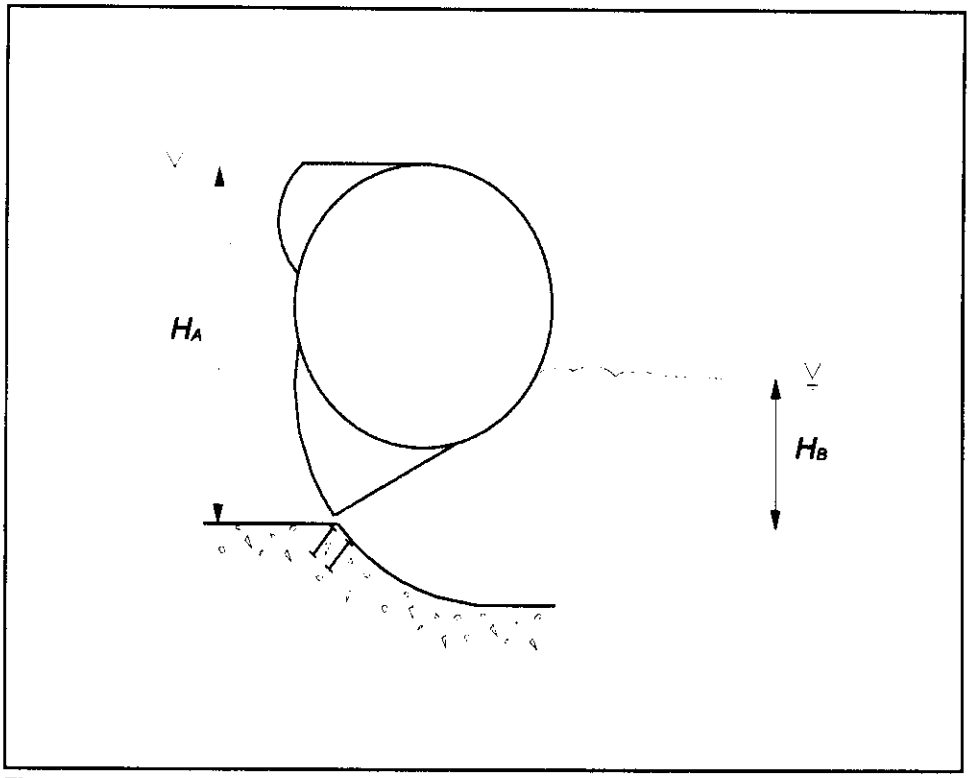

Figure 21. Head conditions

If significant vertical and rotational movements occur in addition to the downstream movement, a reduction factor of 0.85 is applied to the CI. Specifically, if the vertical deflection, ΔV, is greater than 1/8 in.,

$$|\Delta V| > 0.125in. \tag{3.37}$$

and the difference in the downstream motion at the two horizontal rulers, ΔTH and ΔBH, respectively, is more than 1/16 in.,

$$|\Delta TH - \Delta BH| > 0.0625in. \tag{3.38}$$

then the CI is reduced. Therefore, the individual CI is:

$$CI = (ReductionFactor)(CI_\delta) \tag{3.39}$$

Table 5 lists several calculated CIs for three different inspections that took place at Dams 14 and 16.

Table 5. Calculated CIs for downstream deflection.

Lock & Dam	Type	Gate	Run	CI
14	Double Apron	5	1	63
			2	75
			3	75
14	Double Apron	5	1	73
			2	73
16	Single Apron	8	1	70
			2	73

Example: A 100-ft-long gate with a drum radius of 78 in. and a sill elevation of 552 ft was bulkheaded, and downstream deflection measurements were made. The following site conditions existed for the inspection:

	Design Elevations	Current Elevations
Upper Pool	572.0-ft	571.5-ft
Lower Pool	561.0-ft	563.7-ft

The following readings were observed:

	Top horizontal ruler (in.)	Bottom horizontal ruler (in.)	Vertical ruler (in.)
No Head	4.50	5.25	8.125
Full Head	4.1875	5.00	8.0625

So that the differences in readings, Δ, are:

Δ	0.3125	0.25	0.0625

The vertical deflection is less than 1/8 in., and the downstream movement at the two horizontal rulers does not differ by more than 1/16-in.; therefore, the reduction factor of 0.85 is not applied to obtain the CI. The calculation of the CI is based only

on δ equal to 0.25 in., the difference in the readings on the bottom horizontal ruler. The X value is determined using Equation 3.35:

$$(0.25in.)\left(\frac{(572.0-552.0)^2 - (561.0-552.0)^2}{(571.5-552.0)^2 - (563.7-552.0)^2} \right) = 0.33in.$$

The limiting value from Equation 3.36 is:

$$X_{max} = (5.93x10^{-5})\left(\frac{1200^2}{78} \right) = 1.09in.$$

The CI is calculated using Equation 3.1:

$$CI = [100(0.4)^{0.33/1.09}] = 76$$

Table 2 describes the CI as Good.

Multiple Distresses

Each individual distress CI contributes to the overall CI. The amount each distress CI contributes to the combined CI depends on the relative importance of the individual CI. To capture the relative importance of individual CIs, weighting factors are used. Table 6 lists the relative initial weights and the normalized weighting factors used. The weighting factors reflect the opinion of the experts as well as the authors. The normalized weights are defined by:

$$W_i = \frac{w_i}{\Sigma w_i}(100) \tag{3.40}$$

where

$$\Sigma W_i = 100 \tag{3.41}$$

Table 6. Weighting factors for roller dam gate distresses.

Distress	w_i	W_i*	W_i**
Noise, jump, and vibration	9.4	11.0	10.3
Vibration with flow	10.7	12.5	11.7
Torsional misalignment	8.9	10.4	0.0
Rack deterioration	9.3	10.8	10.2
Rim deterioration	11.1	13.0	12.2
Seal/end shield damage	6.5	7.6	7.1
Cracks	17.4	20.3	19.1
Dents	2.3	2.7	2.5
Corrosion/erosion	10.0	11.7	11.0
Downstream deflection	14.5	0.0	15.9

* Downstream deflection excluded
** Torsional misalignment excluded

The combined CI is given by:

$$Combined\ CI = W_1CI_1 + W_2CI_2 + \cdots + W_nCI_n \tag{3.42}$$

The combined CI is calculated using Equation 3.42 unless a crack is found in a critical component. As discussed earlier, if a crack is found in one of the three critical components the combined CI is 30; see Equations 3.23 and 3.24.

Note that when downstream deflection data is not available, the normalized weighting factor for downstream deflection is forced to zero. When downstream deflection data is available, the torsional misalignment normalized weighting factor is forced to zero. Therefore, either the torsional misalignment CI or the downstream deflection CI is used in the calculation of the combined CI.

Previous work by ISU suggests a variable weighting factor should be used for each of the individual distresses. As the CI for an individual distress becomes lower, the relative weight for the distress increases. Therefore, as a distress becomes worse it affects the combined CI more. This means that the normalized weighting factor, W_i, is a function of the CI as well as the relative initial weights, w_i, given in Table 6.

Therefore, relative initial weights are multiplied by a weight adjustment factor that depends on the CI. Figure 22 is a graph of the weight adjustment factor versus the individual distress CI. For CIs in Zone 1, the adjustment factor is 1.0 and

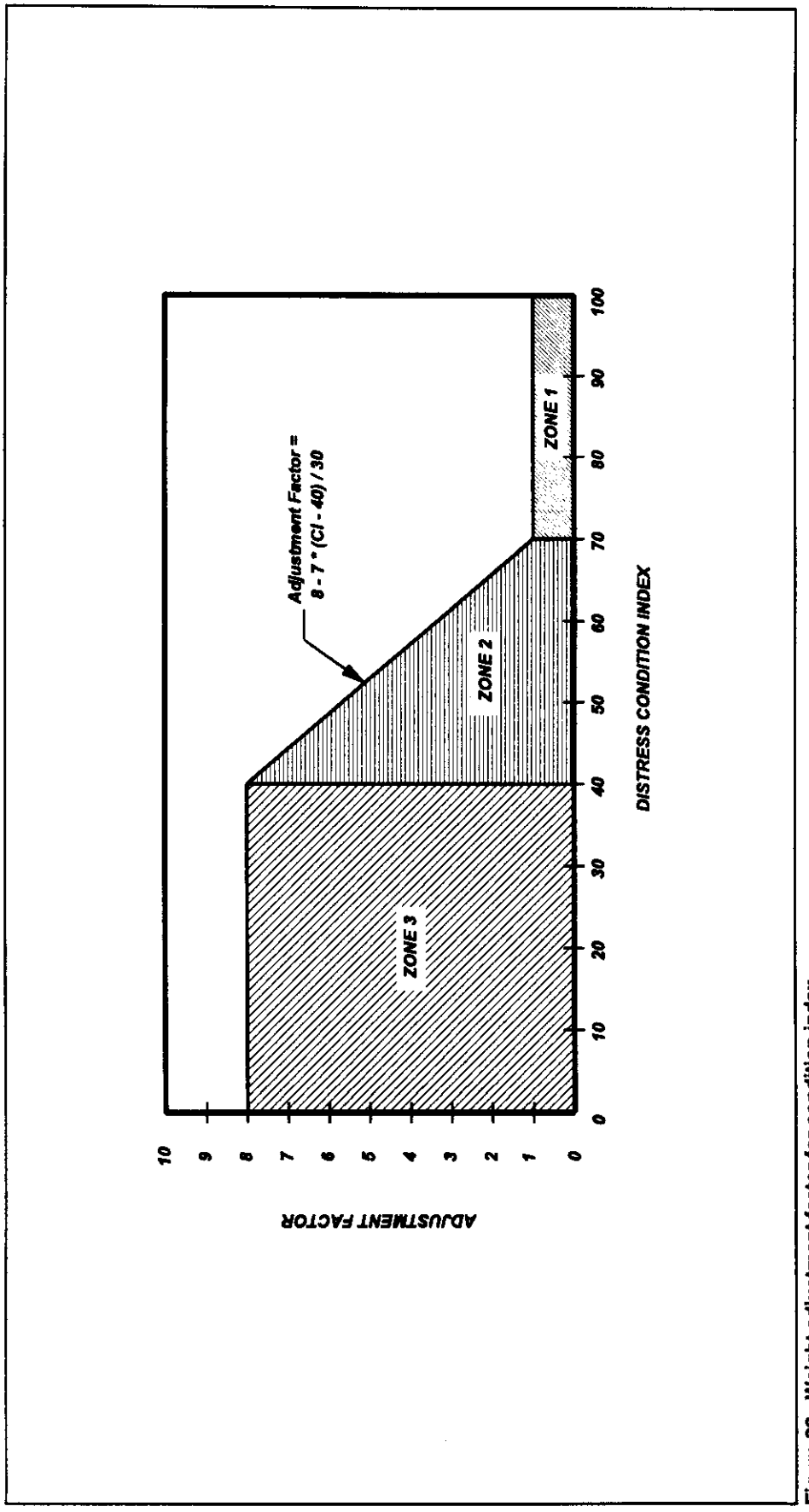

Figure 22. Weight adjustment factor for condition index

the relative initial weight listed in Table 6 is used. If the CI is in Zone 2, the weighting factor varies linearly from 1.0 at a CI of 70 to 8.0 at a CI of 40. If the CI is in Zone 3, the adjustment factor has a value of 8.0. This means that if the CI is 40 or less the relative initial weight is increased by eight times its original value given in Table 6. If any of the individual distresses calculates a CI in Zones 2 or 3, Equation 3.41 must be modified to be:

$$W_i = \frac{(adjustment\,factor)w_i}{\Sigma(adjustment\,factor)w_i} \tag{3.43}$$

Example: Table 7 summarizes an example calculation of the combined CI. The second column contains a set of example CIs for the individual distresses. The third column of Table 7 lists the individual weights for each distress (from Table 6). The fourth column gives the adjustment factors that were calculated using Figure 22. The fifth column lists the normalized weights for each distress, which were calculated using Equation 3.43. As discussed earlier, downstream deflection information is available so the torsional misalignment distress is given no weight in the combined CI. The final column of Table 7 multiplies the normalized weights by the individual CIs. The combined CI is then the sum of all the products given in the final column of Table 7 (see Equation 3.42). In this example, the combined CI is 63, which Table 2 describes as Fair.

Table 7. Example of combined CI calculation.

Distress	CI_i	w_i	adj. fact.	W_i*	$(W_i^*)CI_i/100$
Noise, jump, and vibration	70	9.4	1.0	4.9	3.4
Vibration with flow	70	10.7	1.0	5.6	3.9
Torsional misalignment	73	8.9	1.0	0.0	0.0
Rack deterioration	59	9.3	3.6	17.3	10.2
Rim deterioration	50	11.1	5.7	32.9	16.5
Seal/end shield damage	54	6.5	4.7	16.1	8.7
Cracks	100	17.4	1.0	9.1	9.1
Dents	76	2.3	1.0	1.2	0.9
Corrosion/erosion	78	10.0	1.0	5.2	4.1
Downstream deflection	76	14.5	1.0	7.6	5.8
Combined CI					63

* Torsional misalignment excluded

Summary

Although the initial set of rating rules will require continued monitoring, and revisions are possible, the rules reflect the opinion of experts familiar with roller dam gates. As the inspection procedure is put into practice, suggestions to alter the procedure or the rules may be made and will be implemented as necessary.

More testing and calibration of the rules should be performed. Several site visits that included testing of the procedures and rules were made; however, a final calibration of the rules to expert opinion was not made. If an indepth calibration is performed during a field test, the rating rules may require adjustment. However, it is reasonable at this point to implement the current procedure and rules based on the testing that was performed.

Software has been developed to automatically calculate CIs using data from the inspection form (Chapter 2) and the rating rules presented in this chapter. In addition to using field data, the software can recalculate CIs as part of "what if" scenarios (Greimann et al., May 1994). For example, the combined CI can be recalculated if it is assumed that one or more of the distresses is repaired. This allows the user to assess the overall impact on the CI if repairs are made. User implementation of the software is similar to steel sheet pile, miter lock gates, sector gates, emptying and filling valves, and tainter dam gates.

4 Structural Considerations

During the development of the rating rules, experts considered two distinct criteria: safety—the most critical criterion—and serviceability. Safety-related distresses are discussed in this chapter.

The effect of structural deterioration on safety is difficult to account for in classic structural analysis techniques and is not easily quantified. Therefore, expert opinion is used to develop rating rules that assess structural condition based on subjective safety requirements. This means that rating rules were developed to simulate an experienced engineer making safety judgments based on inspection notes or data.

Certain distresses characterize the structural adequacy and safety more than others. These distresses are more critical to the overall safety of the structure and are called structural distresses. Table 8 gives a listing of the seven roller gate structural distresses.

To alert an engineer to a potential safety problem or to an already existing problem, structural notes are attached to the structural distresses under certain circumstances. Structural notes act as warning flags and appear if: the torsional misalignment CI is less than 55, evidence of relative movement between the rack and pier is recorded, if teeth are damaged, if a crack exists in a critical component, or if the downstream deflection CI is less than 40. Structural notes simply state that the given structural distress may indicate that a serious structural problem exists and further investigation is strongly advised.

Table 8. Roller dam gate structural distresses.

Structural Distress	Brief Description
Rack connections deterioration	Relative movement between rack and pier
Tooth damage	Chipped, deformed, pitted, gouged, or excessively worn teeth
Transverse crack in center 1/3 of downstream drum skin plate	Break caused by flexural tension in the skin plate
Crack in chain anchor	Break in steel that connects chain to gate
Crack in load disc	Break inload disc steel

5 Summary and Recommendations

The inspection and rating procedures described in this report for roller dam gates have been kept simple intentionally. Application of inspection procedures does not require sophisticated equipment. Most measurements can be made with tape measures or rulers. A straightforward inspection form has been developed that documents all the necessary information to calculate the CIs as well as historical information to give the data a context.

Ten individual distresses were identified for roller dam gates. The rating rules that relate the inspection data to the CI are based on the opinion of Corps experts and engineering judgment. The relative importance (weight) of each distress was also established in consultation with Corps experts. A combined CI for a roller dam gate is obtained as the weighted average of the ten individual CIs. A subset of distresses is identified as structural distresses that relate to the safety of roller dam gates. Software has been developed to calculate the CIs automatically when inspection data is entered.

The inspection procedure and rating rules have been reviewed by several Corps experts and have been tested on gates at seven locks and dams on the Mississippi River. Current roller gate rating rules may undergo further modification with implementation.

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Appendix A
Torsional Misalignment Distress Development

The torsional misalignment distress monitors relative torsional rotations of the driven and nondriven ends when the gate is opened. Using a projection device mounted on the gate, marks are made on both ends of the piers when the gate is closed and again at the 6-ft open position (see Chapter 2). Assuming the projection devices are mounted identically on both ends of the gate, the limiting value for X can be developed. Experts have agreed to set the maximum allowable angle of twist, $\Delta\theta_{max}$, between the two ends of the gate at a value that will cause a shear strain in the skin plate at 1/3 of the yield strain,

$$\Delta\theta_{max} = \frac{\Delta\theta_{yield}}{3} \tag{A.1}$$

If the behavior of the gate is approximated as that of a shaft or cylinder in torsion,

$$\Delta\theta_{yield} = \frac{(\gamma_{yield})(L)}{(r_d)} \tag{A.2}$$

where γ_{yield} is the shear strain at yielding, L is the length of the gate in inches and r_d is the radius of the drum in inches. Applying Hooke's law for shearing stresses,

$$\gamma_{yield} = \frac{\tau_{yield}}{G} = \frac{(33\ ksi)}{(\sqrt{3})(11200\ ksi)} = 0.0017 \tag{A.3}$$

where τ_{yield} is the shear stress at yielding and G is the modulus of rigidity of steel. Rewriting Equation A.1 yields:

$$\Delta\theta_{max} = \frac{(0.0017)(L)}{(r_d)} \tag{A.4}$$

The following equations were developed to determine the path of any point on the gate for any rotation, θ,

$$Z^2 = A^2 + B^2 \tag{A.5}$$

in which

$$A = \left[(-2)(r)\left(\sin\left(\frac{\theta}{2}\right)\right)\left(\cos\left(\frac{\theta}{2} - \beta\right)\right) - \left(\frac{4}{10.77}\right)(R)(\theta)\right] \tag{A.6}$$

$$B = \left[(-2)(r)\left(\sin\left(\frac{\theta}{2}\right)\right)\left(\sin\left(\frac{\theta}{2} - \beta\right)\right) - \left(\frac{10}{10.77}\right)(R)(\theta)\right] \tag{A.7}$$

where Z is the total linear distance traveled by a point on the gate that rotates an angle of θ, A is the horizontal distance traveled, B is the vertical distance traveled, r is the radial distance to the point on the gate in inches, R is the gate rim radius in inches, and β is the angle between the top of the gate and the point (Figure A.1).

Equation A.7 was used in an iterative process to determine a relationship between the angle of rotation to create a 6-ft opening, $\theta_{6\,ft}$, and the gate rim radius, R,

$$B = \left[(-2)(r_{la})\left(\sin\left(\frac{\theta_{6ft}}{2}\right)\right)\left(\sin\left(\frac{\theta_{6ft}}{2} - \beta_{la}\right)\right) - \left(\frac{10}{10.77}\right)(R)(\theta_{6ft})\right] \tag{A.8}$$

where r_{la} is the radial distance from the gate drum center to the seal on the lower apron in inches and β_{la} is the offset angle measured from the top of the gate to the seal on the lower apron (Figure A.1). A review of roller gate geometries on construction drawings of 90 percent of the roller dam gates on the Mississippi River determined that the relationship between θ and R for a single-apron gate was

$$\theta_{6ft} = \frac{45}{R} \tag{A.9}$$

and for a double-apron roller gate,

$$\theta_{6ft} = \frac{38}{R} \tag{A.10}$$

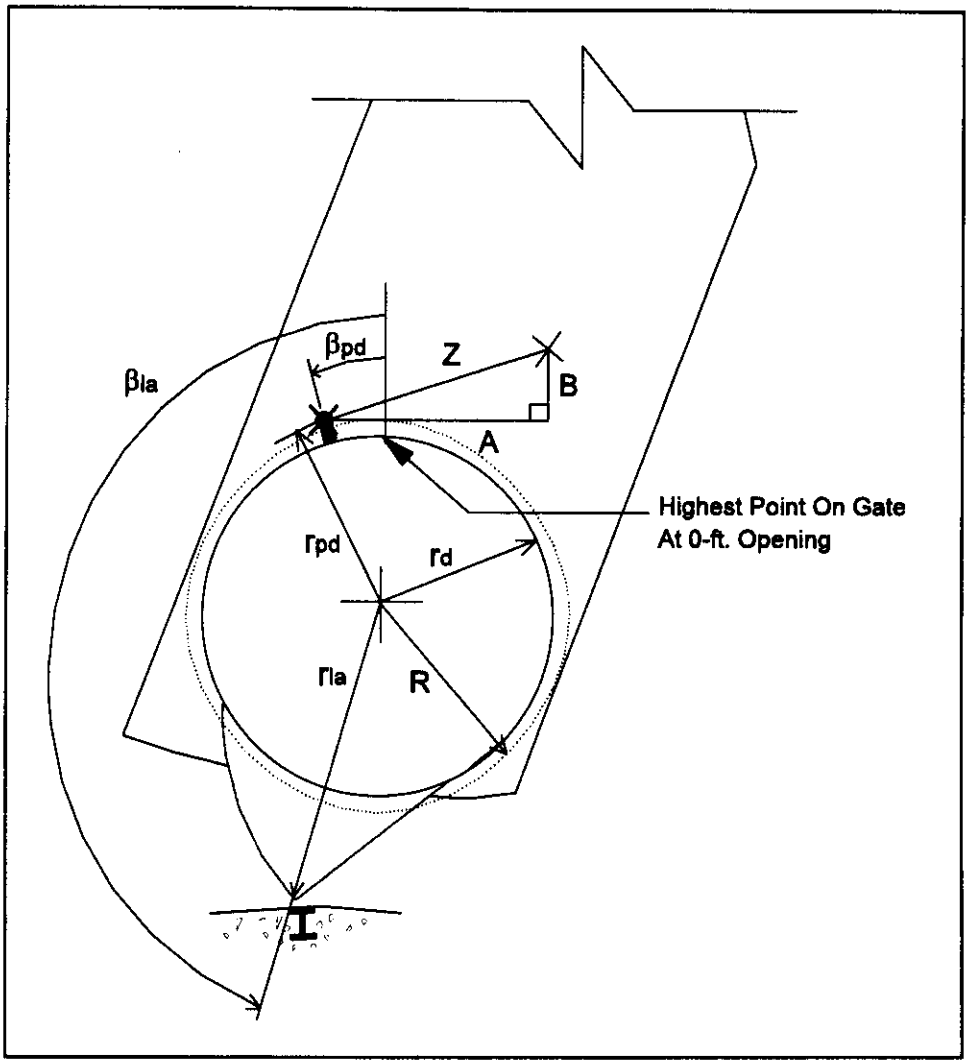

Figure A.1. Torsional misalignment geometric parameters.

Assuming that the nondriven end of the gate lags the driven end, the rotation measured on the driven, θ_{drv}, and nondriven, θ_{ndrv}, ends of the gate when the steel is at 1/3 of yield shear strain are:

$$\theta_{drv} = \theta_{6ft} \tag{A.11}$$

$$\theta_{ndrv} = \theta_{6ft} - \Delta\theta_{max} \tag{A.12}$$

The linear distance travelled by a projection device on the driven end, Z_{drv}, is given by Equation A.5 with r equal to the radial distance to the projection device, r_{pd}, θ equal to θ_{drv}, and β equal to the offset angle to the projection device, β_{pd}

(Figure A.1). The linear distance travelled by the projection device on the non-driven end, Z_{ndrv}, can be found in a similar manner except that θ is equal to θ_{ndrv}.

To simplify the calculation of Z_{drv} and Z_{ndrv}, two assumptions concerning the location of the projection device were made. The first being that the offset angle, β_{pd}, was equal to:

$$\beta_{pd} = \frac{2\ ft}{r} \tag{A.13}$$

The second assumption was that the r_{pd} was between 0 and 12 in. off the skin plate. With β_{pd} between the ranges of:

$$\frac{0\ ft}{r} < \beta_{pd} < \frac{4\ ft}{r} \tag{A.14}$$

the error produced with those two assumptions was found to be ±2 percent.

The limiting value for X, then, is:

$$X_{max} = \frac{Z_{drv} - Z_{ndrv}}{Z_{drv}} \tag{A.15}$$

Graphs of X_{max} versus L were plotted for existing gates. A linear relationship, which was found to depend on R and L, was found to exist between X_{max} and L. A multiple regression analysis was performed for both single-apron and double-apron gates using a first-order interaction model (Devore 1990), creating a single equation for X_{max}, dependent on only R and L, for each case. The resulting limiting value for gates with one apron is:

$$X_{max} = 0.00201 + (1.86x10^{-4})L - (1.88x10^{-5})R - (1.50x10^{-8})LR$$

The resulting limiting value for gates with two aprons is:

$$X_{max} = 0.00233 + (2.19x10^{-4})L - (2.18x10^{-5})R - (1.50x10^{-8})LR$$

Appendix B
Development of Downstream Deflection Measurement

The following development assumes a roller dam gate can be modeled as a uniformly loaded simply supported beam. The maximum bending moment, M, is:

$$M = \frac{wL^2}{8} \tag{B.1}$$

where w is the uniform load (kips/inches), and L is the length of the gate (inches). The uniform load, w, can be expressed as:

$$w = \delta\left(\frac{384EI}{5L^4}\right) \tag{B.2}$$

where δ is the deflection at the middle of the gate (inches), E is the modulus of elasticity of steel (kips per square inch), and I is the moment of inertia (inches^4) of the gate about the axis of bending. Substituting Equation B.2 into Equation B.1 gives:

$$M = \delta\left(\frac{9.6EI}{L^2}\right) \tag{B.3}$$

Flexural strain can be expressed as:

$$\epsilon = \frac{Mc}{EI} \tag{B.4}$$

The horizontal distance to the extreme fiber, c, is approximately equal to the radius of the drum r_d (inches). Substituting Equation B.3 into Equation B.4 gives:

$$\epsilon = \delta\left(\frac{9.6r_d}{L^2}\right) \tag{B.5}$$

Assuming steel with a yield strength of 33 ksi (type A7), yield strain is given as:

$$\epsilon_y = \frac{\sigma_y}{E} = \frac{33ksi}{29{,}000ksi} = 0.00114 \tag{B.6}$$

Rearranging Equation B.5 and substituting in the yield strain condition of Equation B.6 gives:

$$\delta_y = \left(\frac{0.00114}{9.6}\right)\frac{L^2}{r_d} \tag{B.7}$$

where δ_y is the deflection at yield strain. Applying a safety factor of 2 against yielding gives a maximum allowable deflection of:

$$\delta_{max} = \frac{\delta_y}{2} \tag{B.8}$$

If the limiting value X_{max} is equal to δ_{max}, and using Equations B.7 and B.8, the limiting value can be expressed as:

$$X_{max} = (5.93x10^{-5})\frac{L^2}{r_d}$$

A deflection equal to δ_{max} will result in a flexural stress 1/2 of the yield stress, σ_y, resulting in a flexural stress, σ_{max}, equal to 16.5 ksi. This limiting value corresponds well with the normal allowable bending stress of 18 ksi for roller dam gates (*Canalization*, 1939).

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The U.S. Army Corps of Engineers has designed and constructed many lock and dam facilities on navigable U.S. inland waterways. As these civil works structures age, the need for condition assessment and maintenance plans grows. This report focuses on assessing the condition of the roller dam gate structures within the Corp's civilian projects by developing an inspection and rating procedure that describes the condition of roller dam gates in a consistent and uniform manner.

Field investigations were conducted at several sites, and experts from the U.S. Army Corps of Engineers were consulted to form a rating system based on engineering rules and considering the opinions of the experts.

This report describes the general inspection and rating system, including defining a condition index and describing roller dam gate distresses. The report also describes the inspection procedure and the rules for calculating condition indexes for roller dam gates.

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