Evaluating Post-Tensioned Trunnion Girders: A Comparative Study of Scale Model Tests and Numerical Analyses

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ABSTRACT

Water flow in dams is commonly regulated using Tainter or miter gates, which are extensively employed in the navigation network of locks and dams managed by the United States Army Corps of Engineers (USACE). Tainter gates are well known for their effectiveness in managing the flow of water through dam spillways. Post-tensioned Tainter gate anchorages are widely utilized in numerous dams across the nation, particularly within the Mississippi Valley Division (MVD), the Great Lakes and Rivers Division (LRD), the Southwestern Division (SWD), and the Northwestern Division (NWD). Between 2010 and 2017, ten dams underwent testing, revealing that eight of them had failed rods. Out of the 5,371 greased trunnion anchor rods tested, 22 were found to be broken, and 6 had slipped gripping hardware. While the overall failure rate might appear low, a detailed analysis shows that individual anchorage failure rates ranged from 2 percent to 29 percent, potentially affecting anchorage capacity and performance. Apart from the trunnion rods that failed due to breaking or slipped connections, 278 rods (202 on Markland Dam and 76 on Greenup Dam) exhibited significant cantilever bending or corrosion, conditions that can contribute to anchor rod failure. This study aims to establish experimental and numerical methods for post-tensioned anchorages with different rod configurations. Laboratory tests on scaled anchorages, featuring a concrete trunnion girder with nine high-strength post-tensioning rods, were conducted. Finite element (FE) analyses were validated using experimental data, replicating various trunnion rod failure scenarios. The FE results accurately predicted load changes on each rod under different loads and de-tensioning configurations. The findings from this research provide valuable insights into anchor rod failure rates, which can assist district engineers in assessing the current condition of anchor rods and planning proactive maintenance and remediation strategies.

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INTRODUCTION

The United States Army Corps of Engineers (USACE) has a large inventory of dams that employs Tainter gates to control water flow. Tainter gates are considered one of the most suitable types of gates for controlling dam spillways. There is a broad distribution of dams with post-tensioned Tainter gate anchorages across the United States, with the highest population of dams being in the Mississippi Valley Division (MVD), the Great Lakes and Rivers Division (LRD), the Southwestern Division (SWD), and the Northwestern Division (NWD).

O'Donnell [1] presented considerations for the design of prestressed concrete anchorages for large Tainter gates. Concrete with 5000 psi strength is required for piers and girders, except for larger gates where higher strength concrete may be required. The magnitude of prestressing was determined from different load conditions and the actual final load on the prestressing steel should not exceed 60 percent of the minimum ultimate strength of the steel. Due to the losses in steel stress caused by elastic shortening of the concrete, creep, and plastic flow etc., the initial tension on the steel, immediately after seating of the anchorages, should not be exceed 70 percent of the ultimate strength of the steel.

Over the period of 2010 to 2017, ten dams were examined and eight of them were found to have failed rods. Out of the total 5,371 greased trunnion anchor rods that were tested, 22 were found to be broken, while 6 had slipped gripping hardware. Overall, considering all the dams tested, these rates of failure appear to be relatively low. However, a closer examination of the failure rate within a single anchorage provides a different perspective. The failure rate of the rod within the anchorage ranged from 2 percent to 29 percent, which has the potential to impact the anchorage capacity and overall performance. Furthermore, aside from the trunnion rods that failed due to breaking or a slipped anchorage connection, a total of 278 rods (202 on Markland Dam and 76 on Greenup Dam) exhibited significantly bent cantilevers or significant corrosion of the cantilever and anchorage hardware, both of which can lead to anchor rod failure.

Abela and Abela [2] presented a case study on the analysis of an existing trunnion girder and its greased post-tensioned anchors before load testing. The analysis, which evaluated the members' capacities using a finite-element model, also investigated the probability of a critical anchor failing using test data recorded from both nondestructive dispersive wave propagation testing and load testing of similar anchors at other dams. The results of the analysis indicated a higher-than-expected probability of a critical anchor failing, in which a large enough flood event could fail the entire post-tensioned anchorage system. Two contingency plans in which using anchorage replacement and a steel exoskeleton wrapped around the trunnion girder with new anchors were considered.

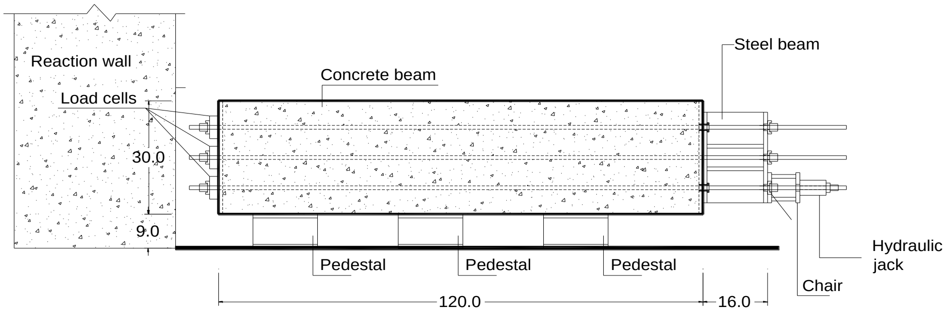
Abela [3] evaluated the adequacy of a passive anchorage system against increased hydrostatic loading using Finite Element (FE) analysis and existing structural and mechanical codified manuals. According to this study, key elements for the evaluation of an existing passive anchorage system include analyzing the behavior of the anchorage system using FE analysis, considering von Mises stress and elongation of the anchorage system, understanding both old and current codified guidance, applying correct classification, and considering the corrosion of embedded anchors. Malik and Zatar [4, 5] worked on structural health monitoring approaches to support waterways infrastructure. Zatar et al. and Nguyen et al. [6, 7, 8] reported on successful approaches for analytical and non-destructive testing of concrete members.

The overarching purpose of this study is to characterize the lifecycle of embedded dam gate anchorages such that risk can be assessed and managed efficiently and effectively by dam owners. The lifecycle analysis may account for relevant geometric, material, operational, and environmental variables. The lifecycle analysis may describe a measure of reliability of anchor rods, or groups of anchor rods if more appropriate, as a function of time given current conditions/knowledge. The analysis should assist dam owners in assessing degradation rates and planning maintenance and remediation strategies proactively. Capacities of the groups of anchor rods are reduced due to failure of some anchor rods in terms of total capacities and force increasing in individual anchor rod. To determine the increasing forces in the anchor rods, physical and numerical modeling is required. This paper presents lab testing and finite element analyses for a scaled model of a Tainter gate structure to evaluate force distribution, or force increase, in remaining anchor rods due to failure of one or a few anchor rods.

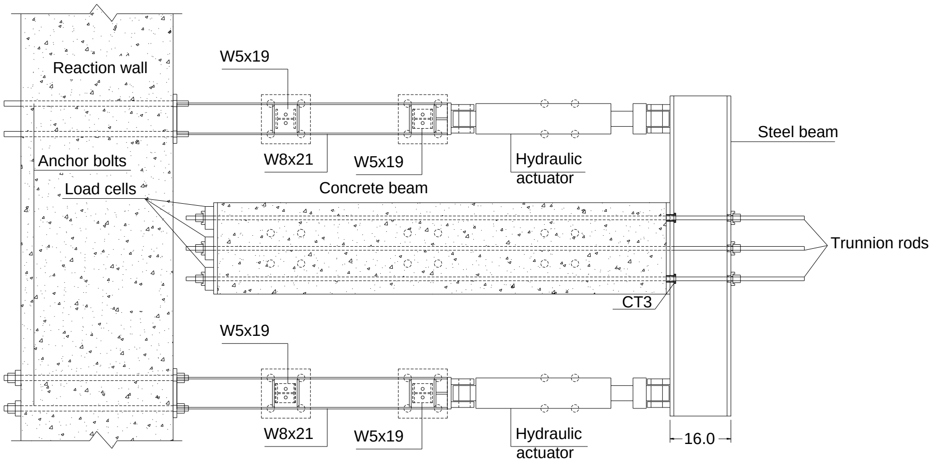
SCALED MODEL OF TAINTER GATE STRUCTURE

The scaled model of Tainter gate structure was developed in the Advanced Materials Testing Laboratory at Marshall University. The lab space is served by a 20-ton overhead crane and the facility is equipped with pre-stressed L-shaped four feet thick pre-stressed concrete strong wall with capacity of 100 kips per anchor, with groups of four anchors spaced at three feet apart, strong floor with four feet thick pre-stressed concrete floor. The strong floor and wall are capable of withstanding 100 kips/interior anchor and 50 kips/exterior anchors and 200 kips/group of anchors in tensile and compressive loading.

The scaled model of Tainter gate structure includes concrete beam, pedestals, steel girder, steel columns and high strength threaded rods, as shown in Figure 1. The concrete beam measures 120 × 24 × 30 in (length × width × height) and sits on three steel pedestals with 3 ft spacing. A steel girder (Figure 2) transfers forces applied by two hydraulic actuators to the trunnion rods and then to the concrete beam. The horizontal distance from each hydraulic actuator to center of the concrete beam is 3 ft. Two steel columns with wide-flange cross section W5x19 are used to support the hydraulic actuators. The concrete beam, steel girders, columns, and pedestals were fabricated in a fabrication facility. Nine high-strength threaded rods are arranged to have 3 rows by 3 columns. The rods are spaced at 8 in thus model trunnion rods in Tainter gate structures. Properties of the threaded rods are presented in Table I. Two hydraulic actuators simulate lateral loads exerted from both water pressure and wind load transferred from the Tainter gate to the girder. The capacity of each actuator is 196 kips, and the corresponding maximum pressure is 5000 psi. The test setup is instrumented by nine load cells placed at the end of each rod at the back end of the concrete beam (Figure 1). Two other load cells are attached to the hydraulic actuators to monitor the transferring forces. All load cells have 50-ton capacity and 2.0mV/V sensitivity. HP Agilent Keysight is used to collect data at a sample rate of 1 sample per second.



a) Side view



b) Plan view

Figure 1. Schematic of the scale model test

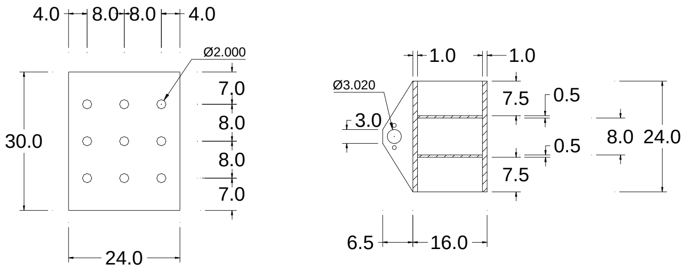


Figure 2. Cross sections of the concrete beam (left) and steel beam (right)

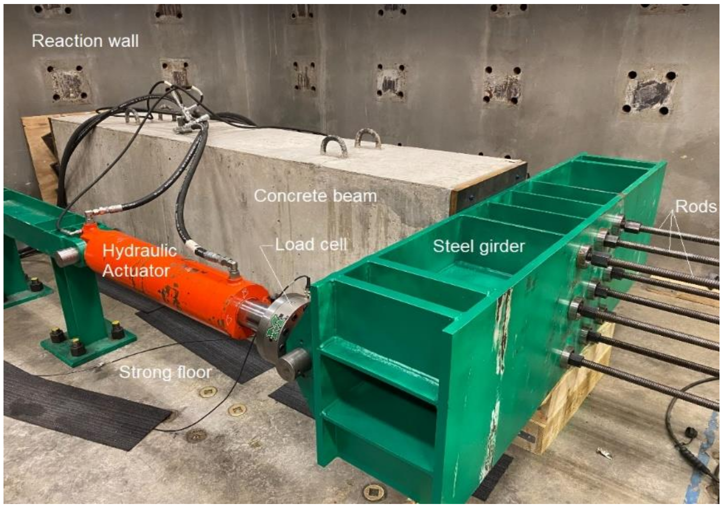


Figure 3. Three-dimensional view of testing system

TABLE I. PROPERTIES OF THE THREADED ROD

Properties	Value
Diameter (in.)	1.0
Cross section area (in.^{2})	0.85
Minimum ultimate strength (kips)	128
Total length (in)	168

TEST PROCEDURE

One of the main purposes of the performed tests is to investigate the distribution of axial forces in the pre-tensioned rods, particularly in the event of failure of any of these rods. The experimental program accounted for having one to three of these rods fail. In the experimental room, de-tensioning of one, two, or three rods was done to reflect cases of failed rods. A scenario in which a maximum of three rods fail represents a severe case where the supporting mechanism could potentially lose up to one-third of its capacity. Considering the maximum number of failed rods is three, more than 30 possible configurations were obtained. The tests were conducted with four levels of pre-tension of the minimum ultimate strength of the rods. Each test includes three steps: 1) pre-tension all rods with tolerance of 1.0 kip between maximum and minimum forces; 2) De-tension selected rods; and 3) Apply forces from the hydraulic actuators. It should be noted that while pre-tensioning one rod, the pre-tension forces in other rods were changed. Therefore, the pre-tension process was repeated until the difference between maximum pre-tension force and minimum pre-tension force is less than 1 kip.

Pressure applied to the hydraulic actuators were increased gradually and were held for a few seconds at four pressure levels: 1200 psi, 1700 psi, 2200 psi, 2700 psi, corresponding to total forces of 92 kips, 130 kips, 169 kips, and 207 kips from the two hydraulic actuators. After finishing the loading process, the hydraulic actuators were unloaded to reach zero pressure.

FINITE ELEMENT ANALYSES

A finite element (FE) model using SSI3D computer code [9] shown in Figure 4 is developed to simulate the scaled model testing. A total of 1440 solid, 752 shell, 9 bar, and 58 interface elements are used to model the concrete beam, steel girder, trunnion rods and contacts, respectively. The interface elements simulate the contact between concrete beam and steel girder and only allow compression stress. De-tensioning the rods is described by de-activating the corresponding bar elements. The de-active bar elements have zero stiffness and no contribution to the behavior of the model. Young's moduli, Poisson's ratios, compressive strength, and yield strengths of the materials used in modeling are given in Table II.

TABLE II. MATERIAL PROPERTIES

Material	Young's modulus (ksi)	Poisson's ratio	Strength (ksi)
Concrete	4095	0.2	4
A36 steel	29000	0.3	60
150 ksi steel	30500	0.3	120

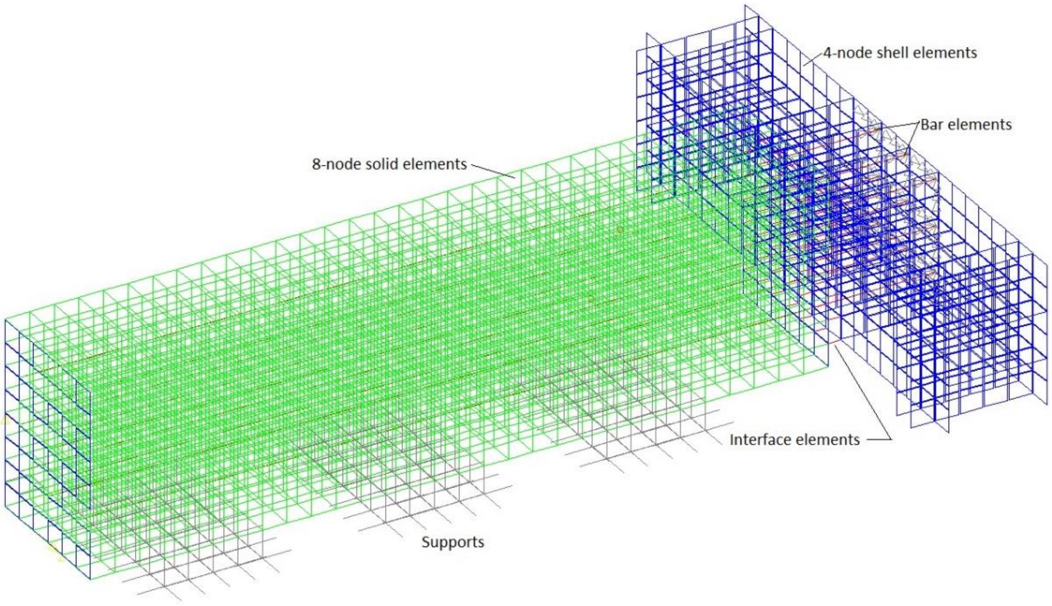
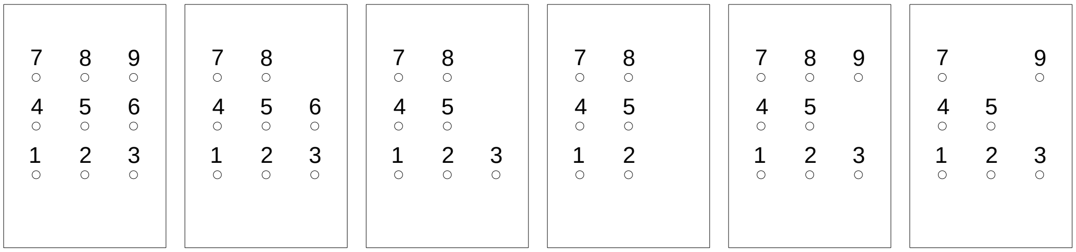


Figure 4. Three-dimensional view of FE model

The rods were numbered from 1 to 9 (Figure 5). Six selected configurations (C1 to C6) are used to compare the finite element analysis (FEA) results with those of the scaled model testing are also shown in Figure 5. The rods which are not existed in configurations C2 to C6 denoted as the de-tensioned rods.

In the first configuration C1 (no rod is de-tension), the average initial pre-tension force obtained from the scaled model tests is 37.7 kips and from the FEA is 38 kips. Tables III and IV present the forces in each rod for selected configurations C1 to C6 for the pre-tension of 30% and pressure level of 2700 psi from the scaled model tests and FEA. The comparison shows that the FEA results are in fair to good agreement with the scaled model tests in all configurations. It also can be observed that the most influenced rods, considered as the rods subjected to highest load, are located next to the de-tensioned rods such as rods #6 and #8 in C2, #3 in C3, #2, #5 and #8 in C4, #3 and #9 in C5, and #3, #5 and #9 in C6.



C1 C2 C3 C4 C5 C6

Figure 5. Configurations in FEA

TABLE III. COMPARISON OF FORCES IN RODS OBTAINED EXPERIMENTALLY AND FROM FEA FOR C1, C2, AND C3 TESTING CONFIGURATIONS

Rod	C1			C2			C3		
	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)
1	39.1	38.5	1.5	37.9	39.8	5.2	36.5	39.4	7.8
2	38.2	38.4	0.7	38.1	40.2	5.6	39.8	40.9	2.8
3	39.2	38.5	1.7	40.3	40.8	1.2	46.0	42.7	7.2
4	39.9	38.6	3.2	39.3	40.4	2.7	38.0	40.3	6.2
5	38.8	38.6	0.8	39.7	40.9	3.0	42.2	42.0	0.7
6	38.9	38.6	0.8	41.0	41.6	1.2	0.0	0.0	0.0
7	40.3	38.7	3.8	40.5	41.0	1.1	39.5	41.2	4.4
8	39.2	38.6	1.4	40.6	41.5	2.1	43.5	42.9	1.3
9	39.3	38.7	1.4	0.0	0.0	0.0	0.0	0.0	0.0

TABLE IV. COMPARISON OF FORCES IN RODS OBTAINED EXPERIMENTALLY AND FROM FEA FOR C4, C5 AND C6 TESTING CONFIGURATIONS

Rod	C4			C5			C6		
	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)
1	36.8	41.7	13.5	38.2	40.2	5.2	37.9	38.0	0.5
2	49.8	54.0	8.6	38.7	40.6	4.9	38.4	41.7	8.5
3	0.0	0.0	0.0	41.5	41.3	0.5	41.2	41.7	1.3
4	37.6	41.9	11.4	38.9	40.4	3.7	39.7	42.1	6.0
5	51.2	54.2	5.8	39.5	40.8	3.4	40.2	42.0	4.3
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	38.2	42.0	10.2	38.7	40.5	4.7	40.5	42.2	4.2
8	51.3	54.1	5.4	39.2	40.9	4.5	0.0	0.0	0.0
9	0.0	0.0	0.0	41.3	41.6	0.8	43.3	42.3	2.3

CONCLUSIONS

This study presents an experimental and numerical investigation into post-tensioned anchorages, specifically focusing on different configurations of de-tensioned rods. The objective of the study was to simulate a trunnion girder using a concrete beam equipped with nine high-strength post-tensioning rods. To replicate the water loads acting on Tainter gates, a test setup incorporating two hydraulic actuators was employed. Various testing configurations were examined to represent different scenarios of trunnion rod failures. Additionally, finite element (FE) analyses were conducted to evaluate the effects of these loading configurations. The findings of this study demonstrate that the FE method accurately predicts changes in load distribution among the rods under various levels of load and de-tensioning configurations. This insight is valuable for improving our understanding and prediction of anchor rod failure rates, thereby assisting district engineers, dam owners, and operators in effectively managing and maintaining dam structures.

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