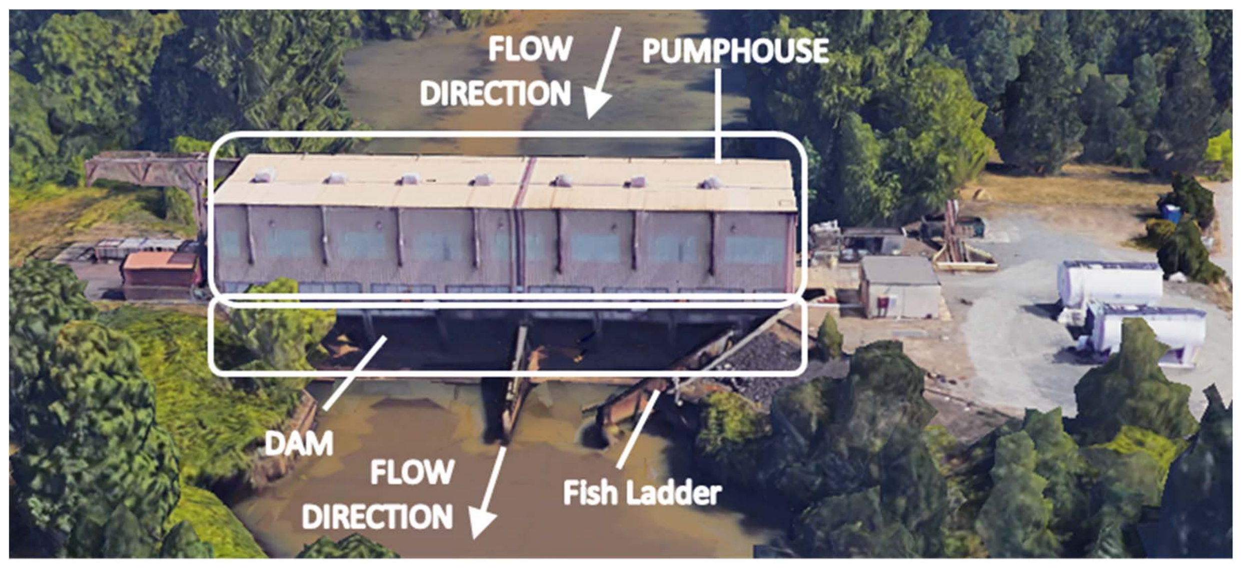
Seismic Assessment and Retrofit of a County Pump Station

Introduction

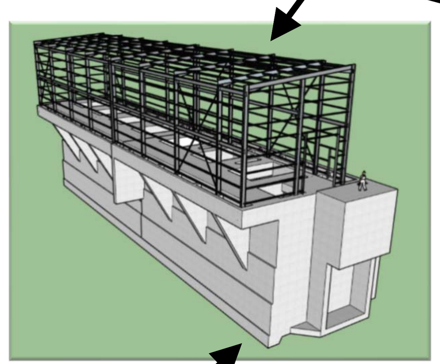
A pump station, owned and operated by a county, is part of a flood control system for three surrounding densely populated cities. The pump station, comprising of a steel pumphouse and a reinforced concrete dam, was built in 1960's prior to seismic provisions were in place.

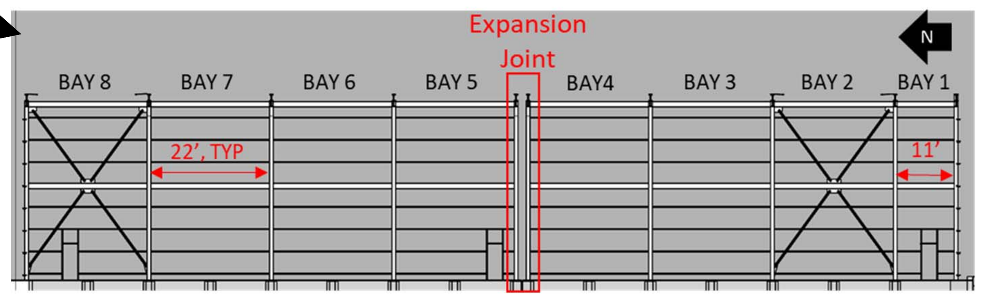
The county requested one of our capstone teams to perform a seismic assessment of, i) the two structures, ii) non structural elements within the pumphouse, and iii) the retaining wall which is part of the fish ladder within the system, and provide retrofit recommendations for any identified deficiencies.



View of Pump Station Looking Upstream

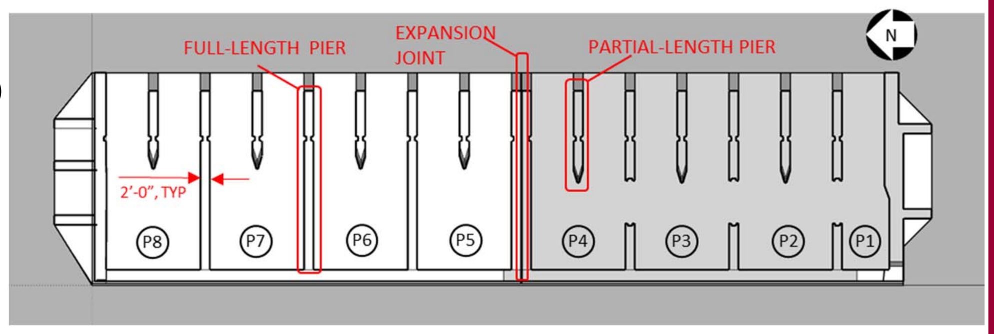
Pump house (steel frame)





Plan View of Pump house

Dam (reinforced concrete)



Plan View of Dam

Project Challenge

Dam and pump house are made of two different materials and both have an expansion joint in the middle. During seismic event, both structures have to move as a unit.

Project Approach and Findings

Team performed Tier 1 and Tier 2 analyses per ASCE 41-13 seismic design guidelines

Tier 1: Gather Information → Complete Checklists → Identify Noncompliant Components

Tier 2: Evaluate Noncompliant Components → Identify Deficiencies → Recommend Necessary Retrofit

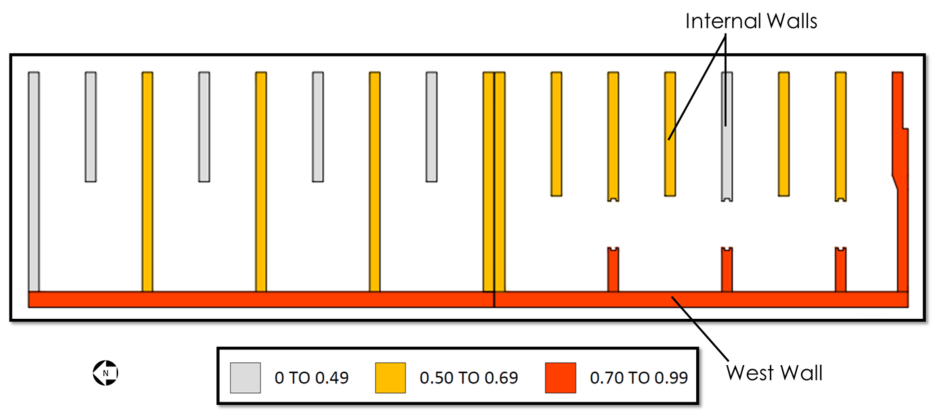
Findings

Structural Assessment of Dam and Pumphouse

Calculated demand (D) and capacity (C) of structural elements. If,

- D/C ratio is < 1, structural element satisfactory
- D/C ratio > 1, retrofit needed

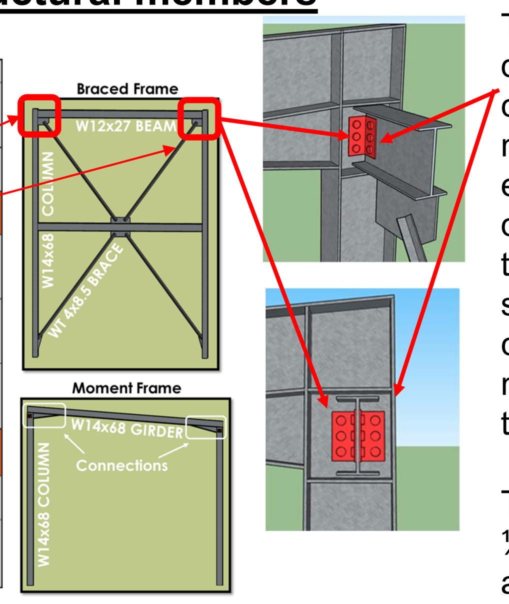
Plan View of Dam with D/C Ratios of walls



Conclusion: Dam has no structural deficiencies.

D/C Ratios of Pumphouse structural members

System	Structural Element	Limit State: Tension	Compression	Shear	Major Axis Bending	Minor Axis Bending	Axial + Bending
Braced Frames	Column Base Plate & Bolts	0.33	0.06	0.16	--	--	--
	W14x68 Column	0.07	0.23	0.12	0.92	0.15	0.95
	W12x27 Beam & Connection	1.66	0.46	0.03	0.05	0.10	--
	W12x36 Beam & Connection	1.66	0.32	0.03	0.03	0.08	--
	WT4x8.5 Brace & Connections	0.92	--	--	--	--	--
Moment Frames	W14x68 Column	0.07	0.45	0.12	0.88	0.17	0.95
	W14x68 Girder	0.01	0.01	0.25	0.81	0.29	--
	Moment Frame Connection	0.66	0.92	--	--	--	--



Thickness of double angle connections not marked on existing design drawings and team could not safely access connection to measure thickness.

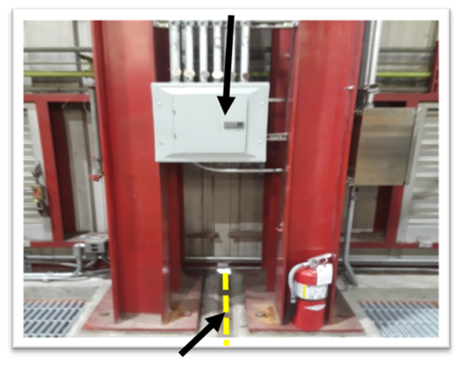
Team assumed ¼" thickness in analysis.

Recommendation:
Double angle connections are potentially deficient at 32 different locations within pumphouse.
Measure thickness of angles on-site at all locations; if thickness is,
- > 3/8" connection is satisfactory
- < 3/8" compare actual thickness to minimum required thickness and replace angles as deemed necessary

Non-Structural Assessment within Pumphouse

Identified various non-structural deficiencies and recommended potential retrofits.

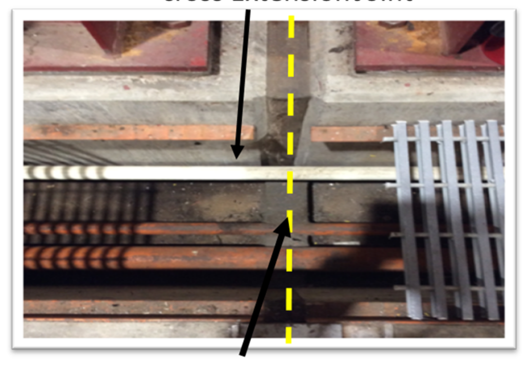
Electrical unit crosses Extension Joint



Extension Joint

Recommendation: Relocate electrical unit to one side of building.

Fuel line, Conduits and Pipes cross Extension Joint



Extension Joint

Recommendation: Fit flexible coupling where pipes and conduits cross extension join

Laterally Unbraced HVAC Unit

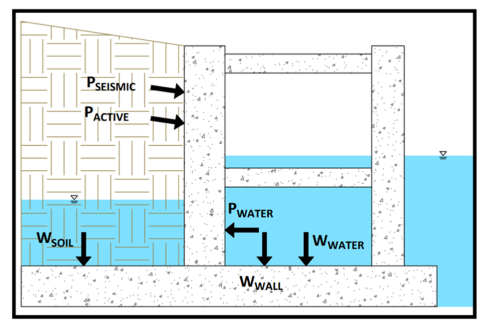
Laterally Unbraced Crane Access Platform

Recommendation: Install lateral bracing to resist seismic forces

Assessment of Retaining Wall

Computed factors of safety against common modes of failure.

Fish Passage



Conclusion: Wall stable in the event of design earthquake

Factors of Safety against overturning 1.7; sliding 1.14; bearing 1.32

Multidisciplinary Nature of Project

- Project required structural, geotechnical and seismic engineering expertise.
- Within structural engineering, project required proficiency in steel and reinforced concrete design.
- A water resources engineer (PE) and an environmental engineer (EIT) served as county representatives.

Public Health, Safety and Welfare Issues

- Pump station is part of a flood control system for three densely populated cities.
- Flooding and liquefaction in the event of an earthquake can have devastating impacts on the residents.
- A fish ladder is an important part of the Facility because of the fish bearing nature of river.

Student, Faculty, Professional Engineer Collaboration

- A team of four civil engineering students were mentored by
  - two faculty members (both PE)
  - two engineers from the county (a PE and an EIT)
  - a structural engineer from industry (SE)
- Team presented proposed work to local Structural Engineering Association in early part of project. Attendees at the event, mostly EIT/PE/SE, provided feedback.
- A panel of judges (5 PEs) selected the project as winner to present at the monthly ASCE local chapter dinner meeting.
- Team presented project to county multiple times; this was attended by PEs from county.

Knowledge and Skills Gained

- **Technical**
  - Developed working knowledge of various design standards and specifications.
  - Read and interpreted as-built drawings, geotechnical reports, USGS seismic design maps.
  - Learned to use a structural analysis software (SAP2000), presentations tool (Trimble Sketchup®).
- **Communication**
  - Developed oral presentation and technical writing skills.
  - Modified content based on varying audiences.
- **Project management and leadership**
  - Learned to manage project schedule, budget and run meetings.
  - Worked as a team to achieve a common goal.

Abstract

Seismic Assessment and Retrofit of a County Pump station

A team of four civil engineering seniors carried out seismic assessment of a pump station owned and operated by a county as part of their capstone project. The pump station is part of a flood control system for the region and came into operation in early 1970's before seismic provisions existed. The pump station consists of a reinforced concrete dam and a steel pump house constructed on top of the dam. The county also requested the team to evaluate the functionality of non-structural elements housed within the pump house and an adjacent fish ladder in the event of an earthquake. Furthermore, the team was asked to research the liquefaction potential of the surrounding soil.

Assessment using the ASCE seismic design guidelines showed that the dam satisfied all seismic criteria with no deficiency. In the case of the pump house, double angle connections that fasten the beams to columns at 32 different locations within the structure were found to be potentially deficient. The team recommended that the county measure the thicknesses of the connections to ensure they met the minimum requirement or replace them with thicker angles. The team found several non-structural deficiencies of the pumphouse equipment and recommended suitable retrofits. The retaining wall forming the fish passage was found to be stable.

The students **collaborated with several professional engineers (PEs)** during the year. They worked under the guidance of two faculty members, both PEs. Two county staff members, one a water resources engineer (PE) and another an environmental engineer (EIT), were the clients. Because the county did not have an in-house structural engineer, a structural engineer (SE) from a private company served as the county representative and subject matter expert and mentored the team. The team presented their project to two professional organizations during the year: Structural Engineering Association (SEA) and American Society of Civil Engineers (ASCE). Several EITs, PEs and SEs attended these events and provided valuable feedback to the team.

The county initiated the project because of its concern for the **public health, safety and welfare** should the pump station fail during a seismic event. Flooding and liquefaction after an earthquake can have devastating impacts on the residents in the three surrounding cities.

This project required knowledge of **multiple disciplines:** structural, seismic and geotechnical engineering. The pump station is constructed of reinforced concrete and steel. Therefore, students had to be familiar with both construction materials, the relevant design principles and codes. Our undergraduate curriculum does not cover seismic engineering. Thus, the advisor and the structural engineer educated the team of the seismic engineering fundamentals necessary for the project. The students had to learn the rest on an as-needed basis with the help of the SE. Stability analysis of the fish ladder required knowledge of geotechnical engineering and seismic engineering.

During the year, the students **gained various knowledge and skills** outside their regular coursework. The students used various building standards, design specifications and a structural engineering software; developed familiarity reading as-built drawings, geotechnical reports, and seismic design maps. In addition to the technical skills listed above, they improved their communication skills through presenting to varying audiences and writing memos, proposal and report to the county. The students also honed their project management and leadership skills through team work, time management, scheduling and art of running professional meetings.

Seismic Assessment and Retrofit of a County Pump station

I. Project Description

Introduction

A local county issued a Request for Proposal to our university's capstone program for the seismic evaluation and retrofit of one of their pump stations (hereafter referred to as the Facility). The Facility came into operation in 1972 before official seismic design provisions existed. The Facility had not been updated or analyzed since its inception to ensure it meets the county's current performance objectives in the event of an earthquake.

Facility Description

The Facility is located near the confluence of three major rivers and is part of a flood control system for the region. The Facility consists of a concrete dam and a steel pumphouse structure as shown in Figure 1. It spans one of the three rivers and protects three cities upstream of the Facility from flood inundation by regulating river flows and by controlling high tides from reaching the river tributaries that lie upstream of the Facility.

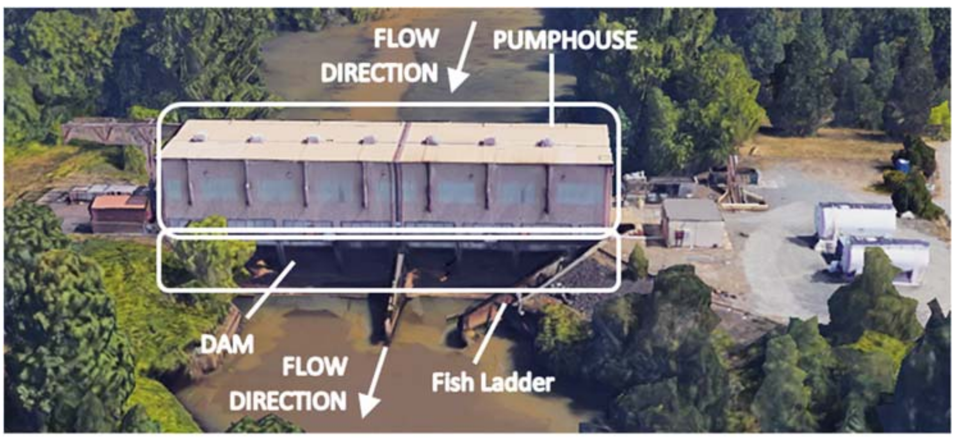


Figure 1. Bird's Eye View of Pump Station Looking Upstream (Source: Google Earth)

Description of Pumphouse: The pumphouse is a steel-framed structure with corrugated steel sheathing and has an exterior length of 165' and width of 36'-8". The roof heights are 29'-6" and 32'-6" above the operating floor on the down and upstream ends, respectively. As shown in the plan view of the pumphouse (Figure 2 - top), a transverse expansion joint separates the pumphouse into two structurally isolated sections with four bays in each section. The roof and walls of Bays 2 and 8 are braced to resist lateral (ie. seismic) forces.

Description of Dam: Like the pump house, the dam also consists of two monolithic reinforced concrete structures separated by a transverse expansion joint (Figure 2 - bottom). The dam rests on a 171' long x 43'-6" wide x 2' thick reinforced concrete mat foundation. The 1' thick concrete slab ceiling of the dam serves as the operating floor of the pumphouse. Each of the two dam sections has four pump bays (marked P1 to P8 in Figure 2- bottom) and the bays are separated by 40' high concrete piers, the full height of the dam. The concrete piers separating the bays, and the longitudinal walls at the east and west ends, resist the lateral forces in the east-west and north-south directions, respectively.

Description of Other Features Relevant to Project: In addition to the dam and the pumphouse, the county was also concerned of the following:

• <u>seismic stability of heavy machinery</u> housed within the pumphouse, which include flood control pumps, impeller shafts, two bridge cranes that travel along rails attached to the pumphouse roof to move heavy equipment (one inside and the other outside the Facility). *This aspect of analysis is typically referred to as the stability of non-structural elements.*

• <u>seismic stability of retaining walls</u> installed at the up- and down-stream of the Facility to facilitate fish migration, one of which is shown in Figure 1.

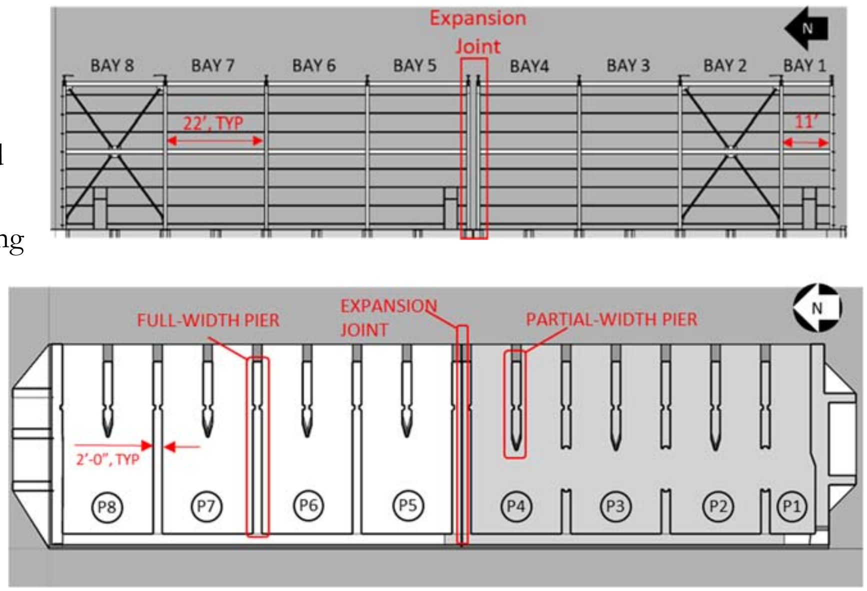


Figure 2. Plan View of Pump house (top) and Dam (bottom)

• <u>liquefaction potential</u> due to the river deposits in the vicinity. *Liquefaction is the inability of a soil to support a structure in the event of an earthquake and occurs commonly in river deposits.*

Project Scope

The county requested that our capstone team perform a seismic assessment of the two structures (pumphouse and dam) and non-structural components within the pumphouse and following that, recommend retrofit options, if needed. The county also asked the team to perform a stability analysis of the retaining walls forming the fish ladder and make preliminary recommendations on liquefaction susceptibility of the site in the event of an earthquake.

Seismic Assessment Process

The team used the two-tiered process specified by the *American Society of Civil Engineers Standard for Seismic Evaluation and Retrofit for Existing Buildings* (*ASCE 41-13*) to perform the seismic assessment. The first tier consists of a screening phase to identify critical areas of the structural and non-structural systems and establish compliance or non-compliance based on the seismic criteria set forth by *ASCE 41-13*. The second tier involves a more detailed analysis of components identified as noncompliant during the screening phase.

Tier 1 (Screening Phase)

The team began the Tier 1 analysis by conducting a site visit and reviewing the as-built drawings to understand the operations and usage of the Facility, identify design constraints, and observe the general condition of the building. They then researched the standard classification of the two buildings, established the target level of performance under an earthquake, and determined the site seismicity risk using United States Geologic Survey (USGS) Seismic Design Maps. The county classified the Facility as a Risk Category IV *(highest possible risk)* because its failure could result in significant flooding of three densely populated cities. The team assessed the Facility for immediate occupancy performance level (*per ASCE 41-13*) in the event of the occurrence of the design earthquake that has a 20% probability of exceedance in 50 years.

Tier 2 (Evaluation Phase)
In this phase, the team analyzed the non-compliant components identified in the Tier 1 screening. This involved more in-depth calculations of the structural demand and capacity of the non-compliant components. For cases in which the demand/capacity ratio (D/C) was found to be greater than one, the component under evaluation was considered inadequate or non-compliant.

For the dam structure, the team computed the D/C ratios of the various walls within the dam. The results are shown in Figure 3. All walls have D/C ratios of less than one, indicating they are compliant. Thus, the team concluded that there are no deficiencies in the dam.

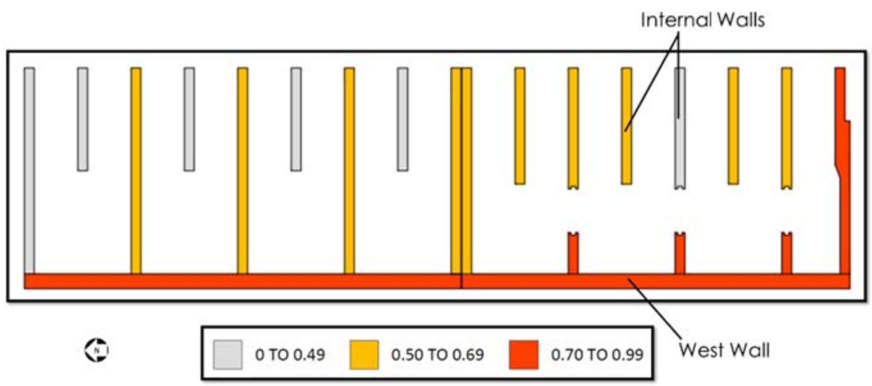


Figure 3. Plan View of Dam Walls and their Corresponding Demand to Capacity Ratios

The team performed a similar analysis for the pump house. It analyzed the steel structure using the Structural Analysis Program, SAP 2000, and computed the demands on the framing members and their connections. The team used the American Institute of Steel Construction (AISC 360-16) Standards for the capacity calculations. Because of space limitation, the D/C results for the pumphouse are presented in the poster.

A double angle connection that fastens the north-south beams to the columns was the only potential deficiency identified for the pumphouse. This potential deficiency is shown in red in Figure 4. Because the thickness of the angle in the connection was not documented in the structural

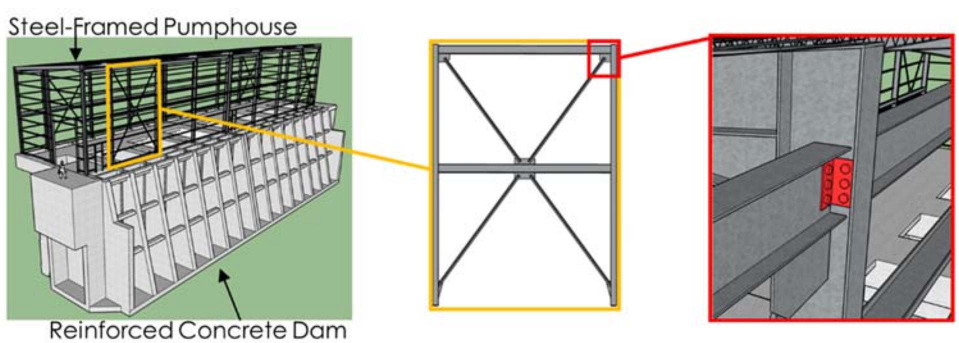


Figure 4. Deficient Double Angle Beam to Column Connection (shown in red)

drawings provided to the team by the county, and the team could not safely access this connection on-site, the team assumed an angle thickness of ¼" in its analysis. There is a total of 32 double angle connections within the pumphouse structure as shown in red in Figure 5.

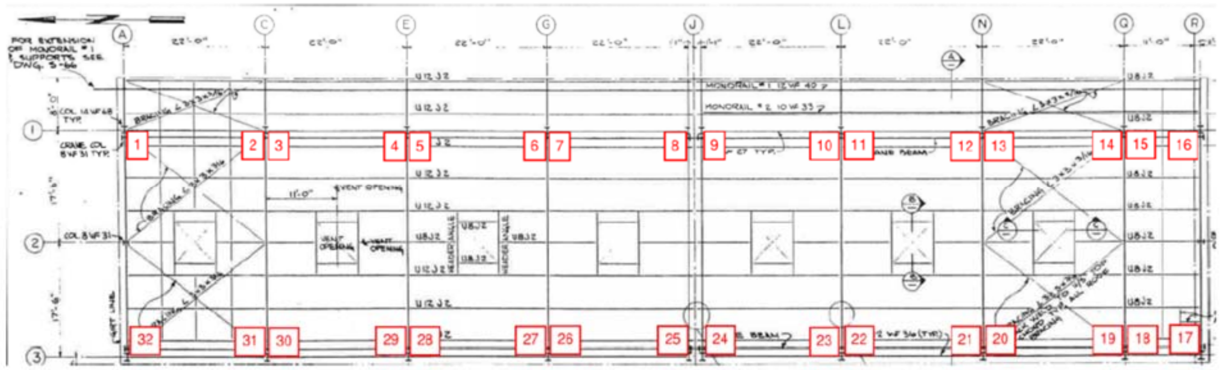


Figure 5. Plan View of Pumphouse showing Locations of Potentially Deficient Double Angle Connections (labeled in red)

Retrofit Recommendations

For the pumphouse column to beam connection deficiency shown in Figures 4 and 5, the team recommended that the existing angle thicknesses be first measured on site. If the angle is 3/8" or thicker, the member is adequate and no retrofit is needed. But if the thickness is less than 3/8", the actual thickness should be compared to the minimum thickness required at each double angle connection location and inadequate angles should be replaced.

Assessment and Retrofit Recommendations of Non-Structural Elements within the Facility

The team assessed the seismic stability of various non-structural elements (described in page 2) within the facility as requested by the county.

The bolted connection of one of the largest pumps (P6 in Figure 2-bottom) onto the pumphouse floor was found to be the most critical non-structural member due to the large seismic mass and eccentricity between the pump and the bolted connection. The team checked the A325 steel bolt connections shown in Figure 6 and found them to be adequate with a D/C ratio of 0.02.

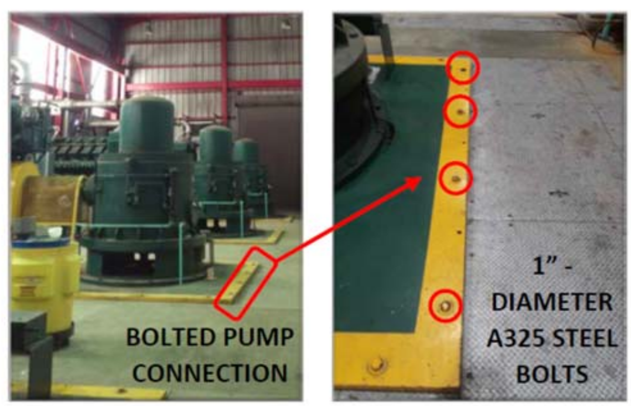


Figure 6. Bolted Connection between Pump Equipment and Pumphouse Floor

Nevertheless, Tier 1 screening revealed non-compliance of various non-structural elements within the pumphouse: a) equipment were crossing the expansion joint without flexible coupling, 2) some equipment were not laterally braced. The team recommended retrofit options for the non-structural elements within the pump house. These are presented in Figure 7; any electrical equipment that is mounted across expansion joint be relocated to one side of the building (top left); all fuel lines and conduits be fitted with flexible couplings (top right); heating, ventilation and air-conditioning (HVAC) units and crane access platforms be braced against lateral motion, (bottom left and right, respectively).

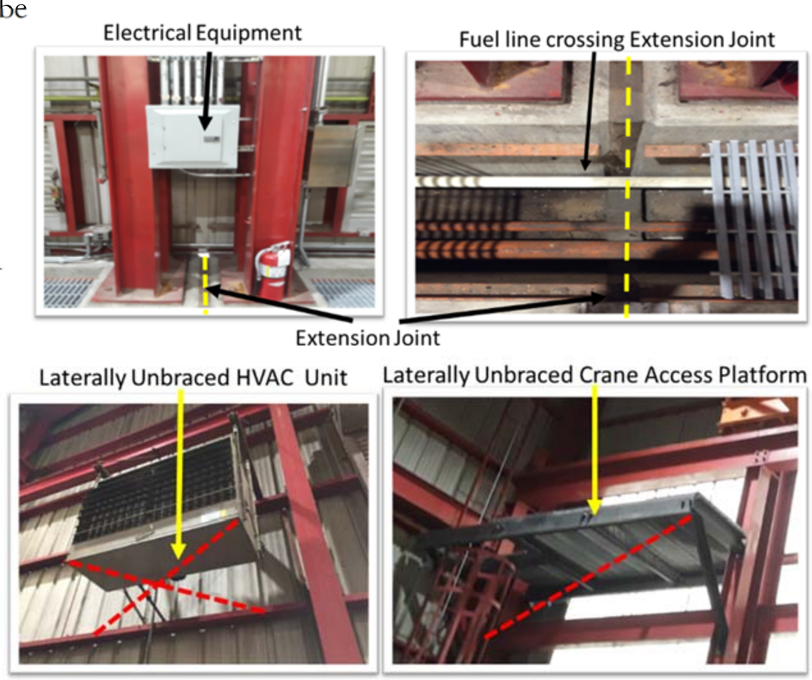


Figure 7. Retrofit Recommendation of Non- Structural Elements within Pumphouse (top: electrical equipment (left) and fuel lines (right) cross extension joint; bottom: unbraced HVAC unit (left) and crane access platform (right))

Stability of Retaining Wall in Fish Passage

As mentioned earlier, the county requested that the team perform a stability analysis of the retaining wall forming the fish ladder. Figure 8 shows a closeup view of the fish ladder at the site. It consists of a counterfort retaining wall with a sloping backfill and strut bracing.

The team performed stability analysis of the retaining wall under loading imposed by the design earthquake. The factors of safety against the most common modes of failure of a retaining wall, namely overturning, sliding and bearing capacity failure, were computed. These factors of safety were found to be 1.7, 1.14, and 1.32 (which correspond to D/C ratios of 0.58, 0.88, and 0.76), respectively. The county deemed these values satisfactory.

Research Finding of Liquefaction Potential

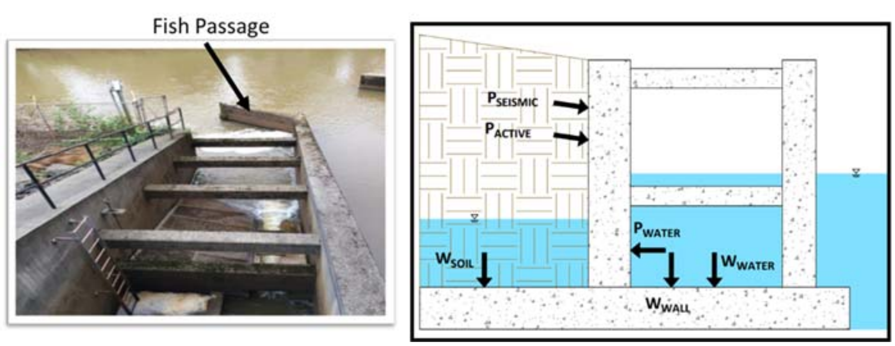


Figure 8. Picture of Fish Passage (left) and Idealization for Stability Analysis of Retaining Wall (right)

The team reviewed the geotechnical reports prepared for the project site and its vicinity. Soil log data presented in the 1969 civil engineering drawings showed that the Facility was constructed on fine to coarse sand and fine silt which is consistent with river deposits. In 2016 a geotechnical engineering firm performed soil analysis 500 ft downstream of the Pump station. Their findings confirmed the soil composition indicated by the original borings. The team conveyed these findings to the county and the liquefaction susceptibility of the Facility in the event of an earthquake. However, the team did not pursue investigating mitigation techniques for liquefaction due to time constraints.

II. Collaboration of Faculty, Students and Licensed Professional Engineers

At our institution, senior Civil Engineering students are required to complete a year-long, real-world, capstone design project. Four students were assigned to this project and worked under the guidance of two licensed faculty members, one the faculty advisor and the other the course instructor. Because the group within the county did not have an in-house structural engineer, an SE from the industry served as the county representative and subject matter expert.

As part of the capstone course, students completed: (1) a project proposal during the fall quarter, (2) the major analysis and design work during the winter quarter and (3) a final report and presentation in the spring quarter. To accomplish these tasks, the student team held two weekly meetings: one with their faculty advisor and the other with both the faculty advisor and the county representatives. Students gave two presentations to the sponsor: the first was late in the fall detailing their design proposal, the second one was late in the spring explaining the final design. These presentations were attended by other professional engineers (PEs) and project managers from the county. The team also presented their work to the local chapter of the Structural Engineers Association (SEA) in winter. They participated in a local annual American Society of Civil Engineers (ASCE) presentation competition which was judged by a panel of PEs. The team placed first and had the opportunity to present at the ASCE local section monthly meeting.

III. Protection of Health, Safety and Welfare of the Public

The project was initiated by the county because it was concerned that public health, safety and welfare would be compromised if the Facility failed during a seismic event. Flooding and liquefaction in the event of an earthquake can have devastating impacts on the residents in the three cities surrounding the project site. Therefore, the county required the assessment to be performed at the level of immediate occupancy of the Facility after an earthquake. The proper performance of the fish passage after a seismic event is an environmental and public welfare concern.

IV. Multidisciplinary Nature of Project

The project encompassed multiple disciplines within civil engineering: structural engineering for the assessment of the Pump Station and within that subdiscipline students had to analyze two different material types, steel and reinforced concrete; geotechnical engineering for the stability analysis of the retaining walls. Our undergraduate curriculum does not cover seismic engineering. The faculty advisor and the structural engineer from the industry taught the team the fundamentals of seismic engineering and the team had to learn more during the course of the project. The county personnel team consisting of a water resources engineer (PE) and an environmental engineer (EIT) served as owner representatives.

V. Knowledge and Skills Gained

The capstone experience helps students develop a variety of important skills needed in practice.

<u>Technical</u> – The students learned to assess and analyze the seismic performance of an existing Facility using the tools listed below.

- As-built drawings
- Building standards - *ASCE Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10), ASCE Seismic Evaluation and Retrofit of Existing Structures (ASCE/SEI 41-13)*
- Design specifications –*American Institute Steel Construction Manual 14th ed.*, *American Concrete Institute Building Code Requirements for Structural Concrete (ACI 318-14)*
- Geotechnical report
- Structural analysis software - SAP2000
- United States Geologic Survey (USGS) Seismic Design Maps

Communication - During the year students developed both writing and speaking skills. In addition to the proposal and final report, the students also provided detailed engineering calculations and technical memoranda to the county throughout the year and received feedback. They were also responsible for sending professional emails to the project liaisons requesting information and to plan meetings and site visits. The team prepared oral presentations for their senior design course, the project sponsor and professional engineering societies. The team developed a detailed Trimble® SketchUp model of the Facility for their presentations and report which worked out to be a powerful way of presenting their project to a more general audience.

Project Management and Leadership - The team organized weekly meetings with the faculty advisor and county representatives. Throughout the year, students took turns serving as the project manager. The project manager was responsible for preparing the agenda, leading meetings, assigning tasks and tracking overall progress.

VI. Summary

A county requested that a capstone team from our civil engineering program perform a seismic assessment of a pump station which was part of a flood control system. A team of four students worked closely with two engineers from the county (PE and an EIT), a faculty advisor (PE) and a structural engineer (SE) from the industry who served as the county's structural representative and subject matter expert. The goal was to maintain immediate occupancy performance level of the pump station following a design level earthquake. Although the Facility was built before seismic provisions were in place, the team found only a single potential structural deficiency at a beam-column double angle connection in the pumphouse. However, the team found several non-structural deficiencies within the Facility and recommended mitigation measures to the county. The students developed valuable technical, communication, and project management skills for their future careers as practicing engineers.