HMS

HEAVY MOVABLE STRUCTURES, INC.

FIFTH BIENNIAL SYMPOSIUM

November 2nd - 4th, 1994

Holiday Inn Surfside
Clearwater Beach, Florida

SESSION WORKSHOP PRESENTATIONS

"SEISMIC RETROFIT AND REFURBISHMENT OF THE BALLARD BASCULE BRIDGE SEATTLE, WASHINGTON"

by DAVID W. KORPI, P.E.
Sverdrup Civil, Inc.

SEISMIC RETROFIT AND REFURBISHMENT OF THE BALLARD BASCULE BRIDGE, SEATTLE, WASHINGTON

by David W. Korpi, P.E.
Sverdrup Civil, Inc.
(206) 822-3300

Abstract

The City of Seattle seismic retrofit program identified the Ballard Bridge as a lifeline route with emergency and life safety importance. The Ballard Bridge, a double leaf trunnion bascule, was constructed in 1916 with no regard for seismic resistivity. Seattle has a design earthquake coefficient of 0.3 g. Recent USGS and AASHTO earthquake mapping shows most of the U.S. with an earthquake hazard risk. Seismic retrofit of bascule bridges is complex because of the inherent sensitivity of operational machinery. Three dimensional dynamic analyses of the pier and movable leaf is complex. Analyses of the Ballard Bridge indicated vulnerable areas included the trunnion girder, movable leaf bottom chord bracing, and the concrete pier. Seismic retrofit designs addressed most of these vulnerable areas in unique ways, while maintaining an operational bridge to waterborne and surface traffic. Retrofits included fixing the trunnion bearing housings to the pier, post-tensioning the trunnion piers, addition of an infill wall between the live load channel piers, addition of longitudinal and transverse stops to the counterweight box, and added anchorage of the control tower base. Refurbishment of the bridge included new bridge grating and bridge railings, refurbished span locks and span drive differentials, and improved counterweight pit access. Construction is scheduled for the second half of 1994.

Introduction

The two recent earthquakes in California (Loma Prieta, October 1989; Northridge, January 1994) caused massive destruction of property and loss of life. More than any other past earthquakes, they have caused public works agencies and municipalities around the country to reexamine their preparedness for a similar event.

Recent USGS seismicity mapping shows most regions around the country to have a significant probability of seismic activity. The highest zones of seismic probability are in California, Alaska, the other Pacific coast states, and the New Madrid area in the central

U.S. However, other areas that have not historically been concerned with earthquakes, are being alerted to their probability in their area -- notably along the eastern seaboard and Appalachian states.

There is now a growing public awareness about earthquakes. This is providing the political incentive, and hopefully the funding, to address some of the public safety problems that earthquakes cause. In the Loma Prieta and Northridge events, bridge structures were seen to be quite vulnerable. Dramatic failures such as the Cypress Viaduct collapse and the Bay Bridge span failure were heavily covered by the media. People around the world witnessed on television the tragic loss of life and the disruption to traffic that a major bridge collapse caused.

With every seismic event on record, data is obtained which furthers the state-of-the-art of seismic design. We understand better all the time what types of bridges and types of construction are vulnerable in an earthquake. Updated versions of the AASHTO Seismic Code are released which cover seismic design of new construction. The problem, of course, is all the older vintage bridges that are still in service that were not designed to resist seismic loads. There is a considerable amount of research work being done in this area as well. The ATC 6-2 Seismic Retrofitting Guidelines for Highway Bridges was published in 1983, and it still remains a good guide for seismic retrofit. New research is being done in order to evaluate different types of retrofit construction on bridge seismic response.

The City of Seattle has been in the process of a Bridge Seismic Study and Retrofit Program since 1992. The purpose of their program has been to evaluate their bridge inventory for seismic vulnerability, to determine the program costs of seismic retrofit, to prioritize the bridges receiving retrofit dollars, and to design and construct the necessary seismic retrofits.

The first step in the study process was to select the most vulnerable bridges of the City's 120 structures. Out of this field, 45 bridges were screened to be critical because of the critical route they served, and their type and age of construction. Prioritization was based upon the following criteria:

- Age of Structure.
- Traffic Volumes.
- Emergency Facility Access.
- Time of Disruption of Service.
- Existence of Alternative Routes.

The types of bridges screened varied widely in structure type -- they included bascule bridges, steel arches, concrete and steel girders, concrete box girders, and timber trestles. One of the major structures that was selected for seismic retrofit study, design, and construction was the Ballard Bridge. This paper describes the seismic retrofit study and the elements of the retrofit and refurbishment design for the Ballard Bridge.

Bridge Description

The Ballard Bridge was built in 1916 over the Lake Washington Ship Canal in Seattle, Washington (See Figure 1). The movable spans are a double leaf trunnion bascule design. The movable span deck is steel grate decking on variable depth trusses. The total bridge length is 292 feet, with each movable leaf being 101 feet and each fixed span 45 feet. The bridge carries 4 lanes of traffic and has sidewalks on both sides of the roadway (See Figure 2).

The substructure consists of 45 foot by 60 foot (plan dimensions) concrete pier houses with two trunnion columns and two anchor columns connected by longitudinal and transverse concrete walls. A trunnion girder connects the movable leafs to the concrete trunnion columns. Live load shoes, at the channel columns, support the movable leafs when the bridge is in the closed position. Large combination spread footings support the concrete columns.

The traffic volumes on the Ballard Bridge are very high -- 54,000 ADT. Because the bridge is located on a main north-south arterial, it functions to carry the major traffic flow to and through the community of Ballard. A seismic emergency that might close this bridge/arterial would be very disruptive. Emergency facilities such as fire, police, and medical facilities located in Ballard make emergency response issues less critical. Because the Ballard Bridge is a movable span, the time to repair any major earthquake damage to the bridge was deemed to be quite long. For the above reasons, the Ballard Bridge was a top candidate for seismic retrofit analysis, design, and construction.

Seismic Retrofit Analyses

The seismic retrofit analysis was based on the AASHTO 1991 Interim "Standard Specifications for the Seismic Design of Highway Bridges"; and the "Seismic Retrofitting Guidelines for Highway Bridges," FHWA/RD-83/007 (ATC 6-2). The following factors were used in the seismic analyses:

- Importance Classification - I; the bridge is classified as an essential bridge.
- Seismic Performance Category - D; based on the essential classification and high acceleration coefficient.
- Acceleration Coefficient - 0.30g; based on regional seismic probability.
- Soil Profile Type - II; soil depth exceeds 200 ft, stable deposits.

The seismic demand, or earthquake load, was determined from an elastic response spectrum analysis of the structure. A finite element model of the Ballard Bridge was created for seismic analysis. The model includes one bascule leaf on a concrete pier acting independently of the opposing pier. In order to fully model the effects of movable leaf, trunnion girder, and concrete pier; the 3D model became very large and complex (See Figure 3). Inherent in this model were assumptions that the center locks that tie the bascule leafs together will fail and that the leafs will be in the closed position during the design level earthquake (DLEQ).

Several computer runs that combined different assumptions about soil characteristics, pier stiffness, and the bascule to pier connections were analyzed in an attempt to envelop seismic response for the DLEQ. These analyses did not consider vertical seismic response, since vertical response is not typical seismic design practice. However, vertical movement associated with the bridge opening is resisted by mechanical equipment only, therefore the bascule leaf may bounce off its live load shoes during an earthquake. The bridge was not modeled nor analyzed in the open position. There is a probability that the DLEQ may strike when the bridge is raised but it is more remote. Because of the nature of a bascule bridge, it would be very vulnerable to an earthquake in the open position.

This is reflected in the current AASHTO code that the seismic loads be one-half the DLEQ in the open position. This condition may be designed for in new movable bridge construction, but is impractical and cost prohibitive for retrofit of older structures.

The bridge components were then analyzed for their strength and compared with this earthquake force. Member capacity was calculated based on ultimate strength design as provided by AASHTO. The ratio of member capacity to demand, the C/D ratio, was calculated according to the ATC 6-2 criteria and is an indicator of a members' ability to withstand the forces and displacements associated with the DLEQ. Some additional non-ATC 6-2 C/D values were calculated for this bridge in order to investigate steel members. A C/D ratio of 1.0 or greater means that the member should withstand the DLEQ demand, while a C/D ratio of less than 1.0 means that the member is vulnerable to failure.

A geotechnical evaluation of the bridge site was performed by the soils consultant to determine what site coefficient was appropriate and whether the site soils might liquefy. For the Ballard Bridge, the geotechnical analysis determined that there was low probability of soil liquefaction at the site. The soils consultant also provided the soil spring stiffnesses to be used in modeling the foundation response.

Seismic Behavior of the Bridge

The bascule bridge structure has a massive concrete pier base. The movable leaf is much lighter and the truss steelwork is inherently more flexible than the concrete piers. The counterweight box adds great mass to the rear of the movable leaf. The trunnion girder connecting the movable leaf to the pier is relatively flexible in torsion. The overall center of gravity of the combined assembly is just back of and lower than the trunnion. Because of the mass and stiffness distribution of the structure, the periods of the first four modes of vibration are each less than 0.34 seconds. These periods are very low and the corresponding accelerations from the response spectrum are 0.75 g's. This is equivalent to saying that the bascule bridge will experience 0.75 g-forces in the DLEQ per this analysis.

Because of the flexibility of the trunnion girder in torsion, a predominate mode of vibration was the longitudinal excitation of the movable leaf. This caused extremely high forces in the leaf and trunnion girder, on the order of 1.2 g's based on the leaf weight.

Analyses Results

The following C/D ratios (See Table 1) were computed by the ATC 6-2 guidelines for seismic retrofit and they indicate the "as-built" condition of the bridge. The ratios show the capacity of the bridge members divided by the earthquake load (or demand) on those members.

Description		As-Built C/D
Trunnion Girder	- Flanges	0.1
	- Web	0.6
Trunnion Shoe Connect.	- Shear	0.2
	- Tension	0.03
Lattice Members		0.6
Bottom Lateral Bracing		0.4
Counterweight Bracing		0.3
Concrete Pier Beam	B8 - Moment	0.7
	B7 - Moment	0.3

Table 1. C/D Ratios for the Pre-Retrofit "As-Built" Bridge.

Seismic Retrofits Designed

The following seismic retrofits were selected for final design and construction:

- Trunnion Bearing Encasement
- Counterweight Restrainer
- Counterweight Bracing Plates
- Channel Pier Wall
- Tower Strengthening

Trunnion Bearing Encasement. The trunnion girder and the top of the trunnion pier around the girder were seen to be the weakest member in the support of the movable leafs (See Photo 1, Figure 4, and Figure 5). A retrofit was designed to correct this problem by partially encasing the trunnion bearing in the pier pocket that reduces torsion in the trunnion girder. The top of the trunnion pier will be post-tensioned with short P/T bars. Special care was taken to maintain the functionality and lubrication of the bearing case.

Counterweight Restrainers. Another means was devised to eliminate the tendency of the bridge to slide off the trunnions in addition to the trunnion bearing encasement. This extra retrofit was done to provide a degree of redundancy for the load transfer. This other retrofit was the restraint of the counterweight in the closed position (See Photo 2, Figure 6, and Figure 7). The restrainer will consist of large plates bolted to the bottom of the counterweight box and to the pier wall. These plates will engage when the bridge is closed, and will allow for engagement with up to about one foot of vertical lift-off of the bridge.

Counterweight Bracing Plates. Between the live load shoes and the counterweight box at the bottom chord of the leaf there exists nominal cross bracing. This bracing was found to be highly overstressed in the analysis. This is also an important set of bracing for the lateral resistance of the leaf. For the seismic retrofit, this bracing will be strengthened as required by the addition of cover plates.

Channel Pier Wall. At the channel piers and between the live load shoes, a new infill concrete wall will be placed (See Photo 3, and Figure 8). A major load deficiency from the seismic analysis was the lateral load capacity of the live load shoes. Instead of strengthening the live load shoes, it was decided to use an infill shear wall with a "girder stop" that slips into the top of the wall. Through this mechanism, the seismic lateral loads are transferred from the leaf and into the pier.

Tower Strengthening. The control tower on the southeast corner of the bridge is vulnerable to being dislodged in an earthquake. The retrofit designed for this condition is to add post-tension bar anchor bolts to the base to tie it down to the pier.

The pier consists of massive concrete beams, columns and walls that have little steel reinforcing and poor confinement. The uncracked section capacity for many pier members is greater than the cracked capacity which means that member failure may be brittle, instead of ductile. Brittle failure is undesirable because the structure cannot withstand too much damage before sudden and catastrophic collapse. However, the analysis shows that the concrete piers have about enough strength to withstand the DLEQ.

The bottom chord bracing on the movable leaf will be severely overstressed in the DLEQ. The retrofit strengthening of the bottom chord bracing will not be included in the current phase retrofit program, but will be postponed to a later phase program. This was deemed to be prudent because little technical data and historical documentation exist to suspect that steel members perform poorly in earthquakes.

The span machinery that moves the bascule will not be retrofitted during the present phase program and may be damaged during an earthquake. However, there are plans in the near term to replace the operating machinery and there will be an overhaul of some of the machinery during this construction project.. At the time when the machinery is replaced, the full consideration of seismic resistivity may be incorporated into its design.

Post - Earthquake Inspection Manuals

A Post-Earthquake Inspection Manual was written to be used by City personnel in inspecting the bridge after an earthquake. It was written assuming the earthquake could occur before any retrofits were done, so therefore, the bridge may sustain considerable damage. The manual contains general information about the bridge; a bridge plan, elevation, and details; locations of expected earthquake damage based on the seismic analysis; a checklist of items for the staff to inspect; and a decision matrix with criteria for making a decision to close the bridge or allow it to remain open for traffic.

The City has assigned their staff with certain bridges to inspect after an earthquake, and this staff will have this manual and other emergency gear with them in their vehicles and at their homes. In the event of an earthquake, the plan is for the staff to make an inspection of the bridge structural condition in about 4 to 8 hours. After this initial inspection, attention can be focused on damaged or closed bridges, to do what is necessary to get them back in service. They expect to have a qualified team of engineers and bridge inspectors perform the follow-up inspections. The bridge electrical and mechanical systems will also require inspection by qualified personnel to determine whether these systems are damaged in an earthquake before ever attempting to operate the span.

Maintenance Items

In addition to seismic retrofit construction, several refurbishment items were included in the construction contract package.

The existing deck grating on the movable leafs had deteriorated, therefore, it will be replaced with new 5-inch deep, heavy 4-way bridge grating (See Figure 9). The support framing over the roadway stringers will have to be modified to accommodate the new deck. The existing decking is 2-inches deep with 6-inch deep ancillary framing. The new decking will be 5-inches deep with 3-inch deep framing.

The roadway curb will be replaced at the same time to facilitate construction (See Figure 10). The curb and deck grating were designed to be removed and replaced on a panelized basis (i.e.: floorbeam to floorbeam.)

In addition to the new decking and curbs, there will also be new steel tube guardrails installed on the leafs (See Figure 10). These rails will be attached to the steel tube curbs that will allow some torsional flex upon impact, thereby affording impact protection to the upstanding trusses.

At center span, the span locks will be rehabilitated to provide new bushings in the span lock machinery, shafts, and lock bar. The lock bar will be machined to receive new wear strips, and the receiver will be remachined. Dry lubricants are specified at the lock mating surfaces.

The span drive machinery will be partially refurbished. The differentials will be removed (one is presently not functioning properly) and overhauled with selective changeout of new bushings, couplers, and spot machining as required.

Access to the counterweight pit will be improved with the addition of new steel ladders and landings at the face of the pier behind the pier protection. This work vastly improves the safety of accessing the pit over what is currently being used. It is also required because the new infill wall blocks normal access to the pit.

Construction Considerations

The high traffic volumes and the importance of the Ballard Bridge make traffic impacts during construction a major concern. In order to alleviate most of the lane closures and construction delays as possible, the specifications require the work be done on the movable leafs in an eight-week period at night. The bridge will be closed to surface traffic from 7:00 PM to 6:00 AM for the construction during this period. The contractor will also be allowed to work during the day but with no lane closures. The bridge will be on a 4-hour notice of opening for waterborne traffic and no double leaf openings at night during this period. It is believed that all the work on the bridge deck can be done at this time. A select number of lane closures will be allowed at other times, but only during non-peak hours of the day.

Construction is scheduled to begin in the fall of 1994, and expected to take 28 weeks. Construction costs for the seismic retrofit and maintenance refurbishment work is not available at the time of this writing.[1]

Conclusion

The overall result of the Bridge Seismic Study and Final Design project is a reasoned approach to evaluating the safety of the City's bridges and prioritizing which bridges should receive seismic retrofit dollars. The Ballard Bridge, because of its high traffic volumes, its importance, and its seismic vulnerability, proved to be an excellent candidate for seismic retrofit. The seismic retrofits selected should improve the probability that the bridge will remain standing and not collapse after an earthquake, and should also permit emergency vehicles use after an earthquake. The bridge will not be brought up to the current AASHTO code level, nor will all the weak details that are inherent in the bridge be removed, but instead strong "load paths" have been designed to keep the earthquake loads from damaging the existing construction.

At the present time, the City of Seattle is aggressively under way on a seismic retrofit construction program for these needed retrofits. In this way the City will derive the real benefits of the all their preparations for earthquakes.

Acknowledgments

Special thanks go to the great people at the Seattle Engineering Department who have made this project a success: Frank Yanagimachi, Dan McKillop, Richard Miller, Ron Nieforth, Linda DeBoldt, and Steve Ferkovich,. Special consultants on the project were Bob Currie, Jim Gates, Paul Grant, Milt Stafford, and Paul Bandlow.. Engineering staff who did all the analysis and design work were Doug Kirkpatrick, Kent Ferguson, Tony Lynch, Paul Bott, and Tom Mahoney.

---

[1]Bid prices for the work should be available at the Symposium in November 1994.

Author

David Korpi, P.E. is a registered structural engineer with 18 years experience in bridge engineering, and a graduate of Washington State University, 1976. Mr. Korpi is a Project Manager with Sverdrup Civil, Inc., and he was the project manager for the Seattle Bridge Seismic Retrofit project; which included three bascule bridges: Ballard, Fremont, and University. He was also responsible for the heavy machinery design of the West Seattle Concrete Swing Bridge, and the machinery QA/QC checking for the First Avenue South Bascule Bridge -- all in Seattle, Washington. Mr. Korpi resides in Edmonds, Washington with his wife and three children. His hobbies include fishing, camping, golf, baseball, his kids' sports teams, and occasional attempts at home improvement.

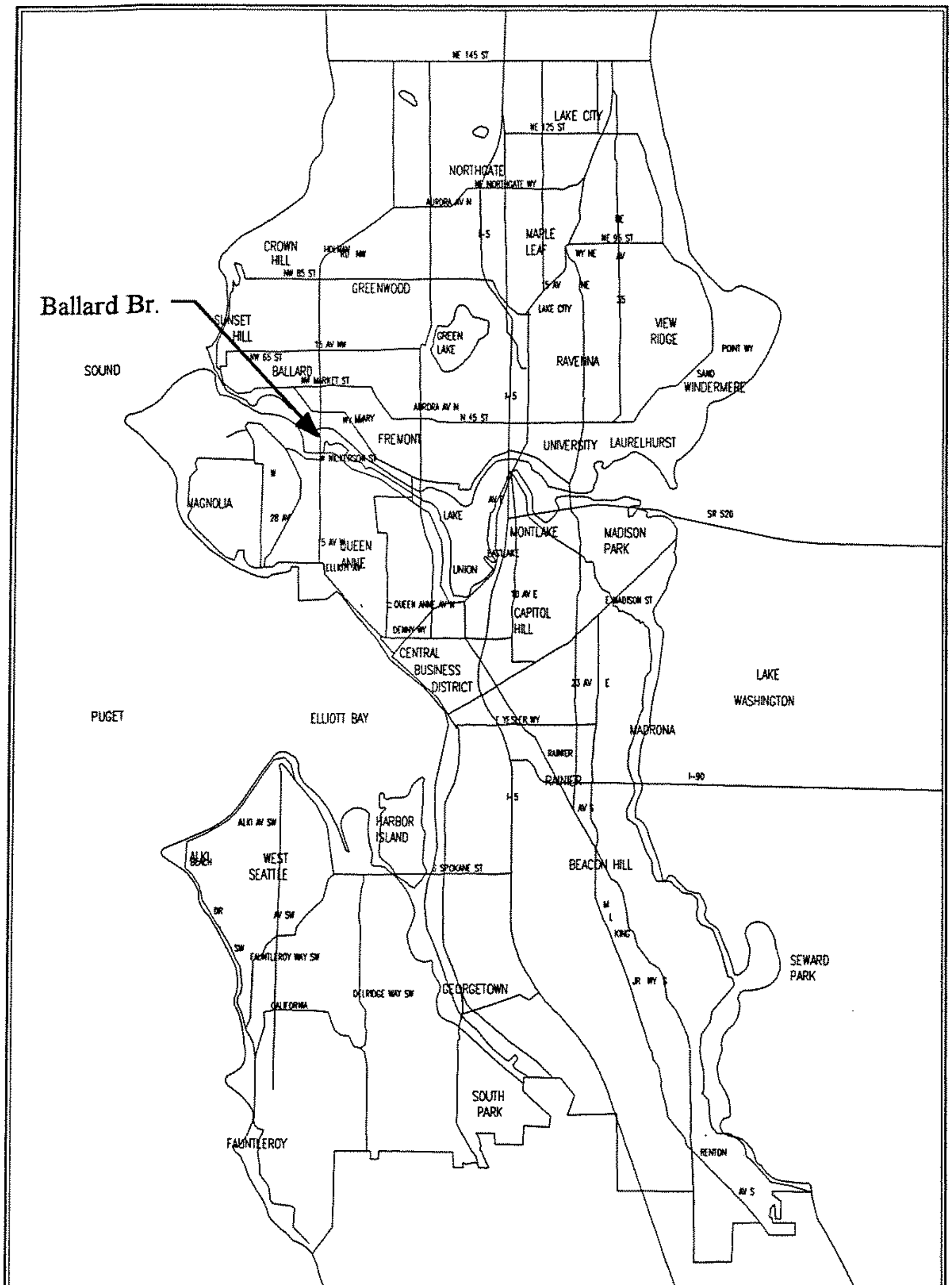

Figure 1. Vicinity Map.

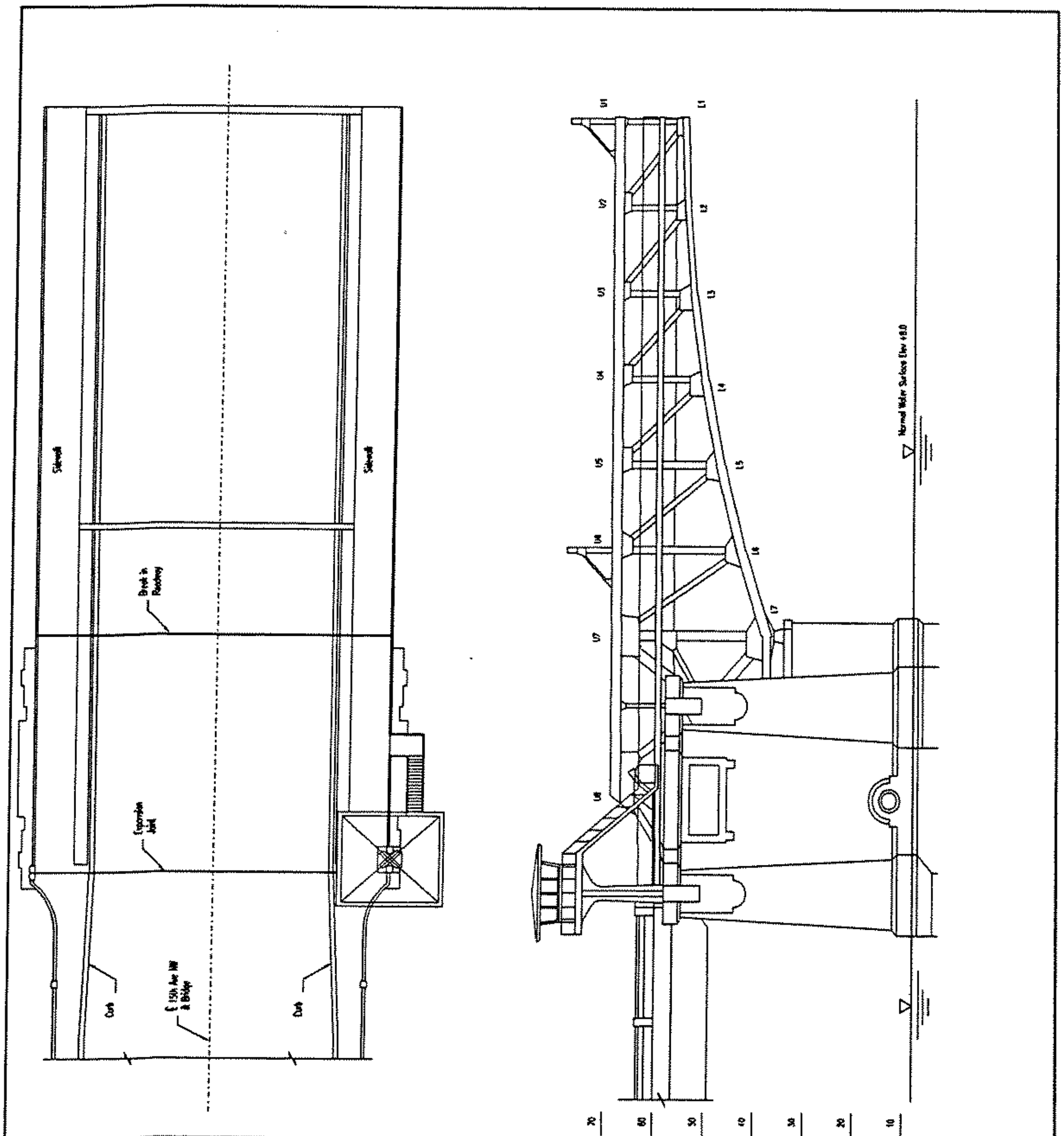

Figure 2. Plan and Elevation of the Bridge.

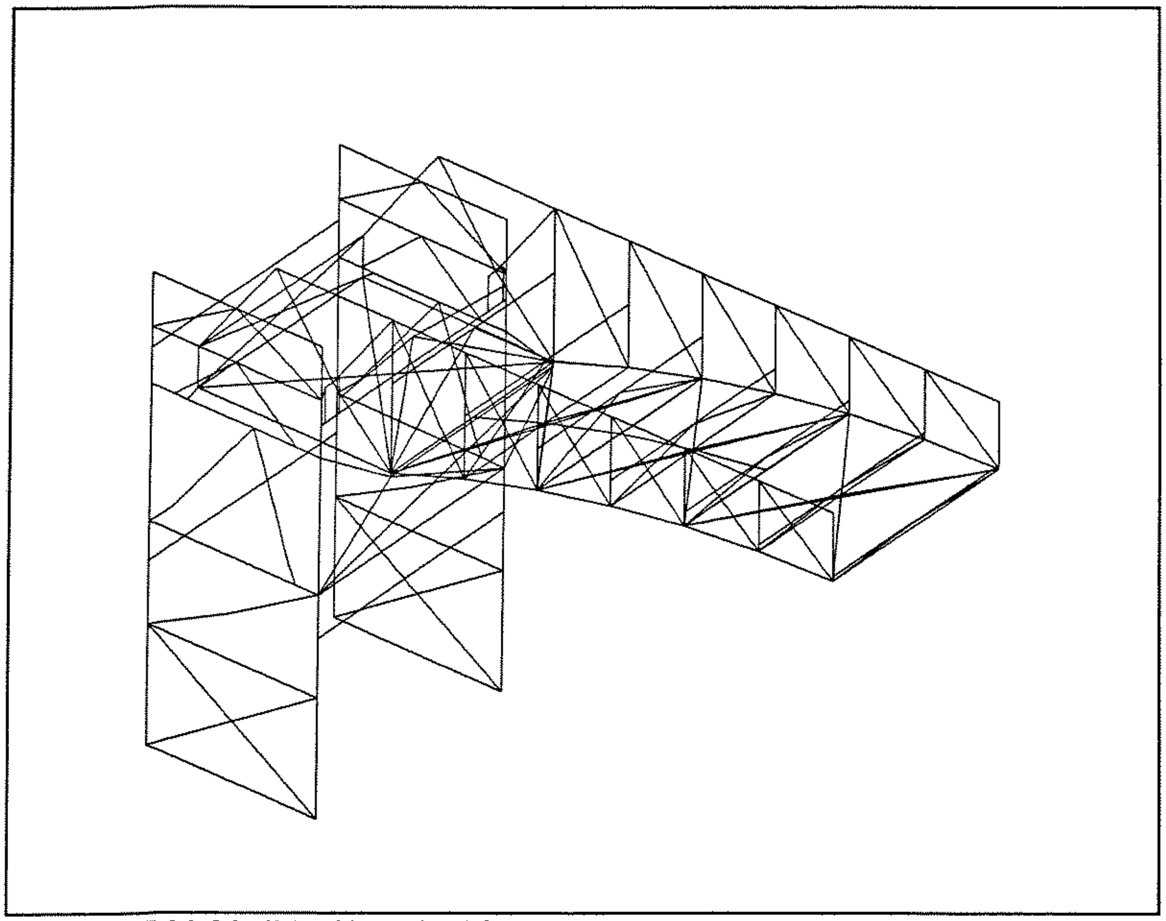

Figure 3. 3-D Model of Movable Leaf and Concrete Pier.

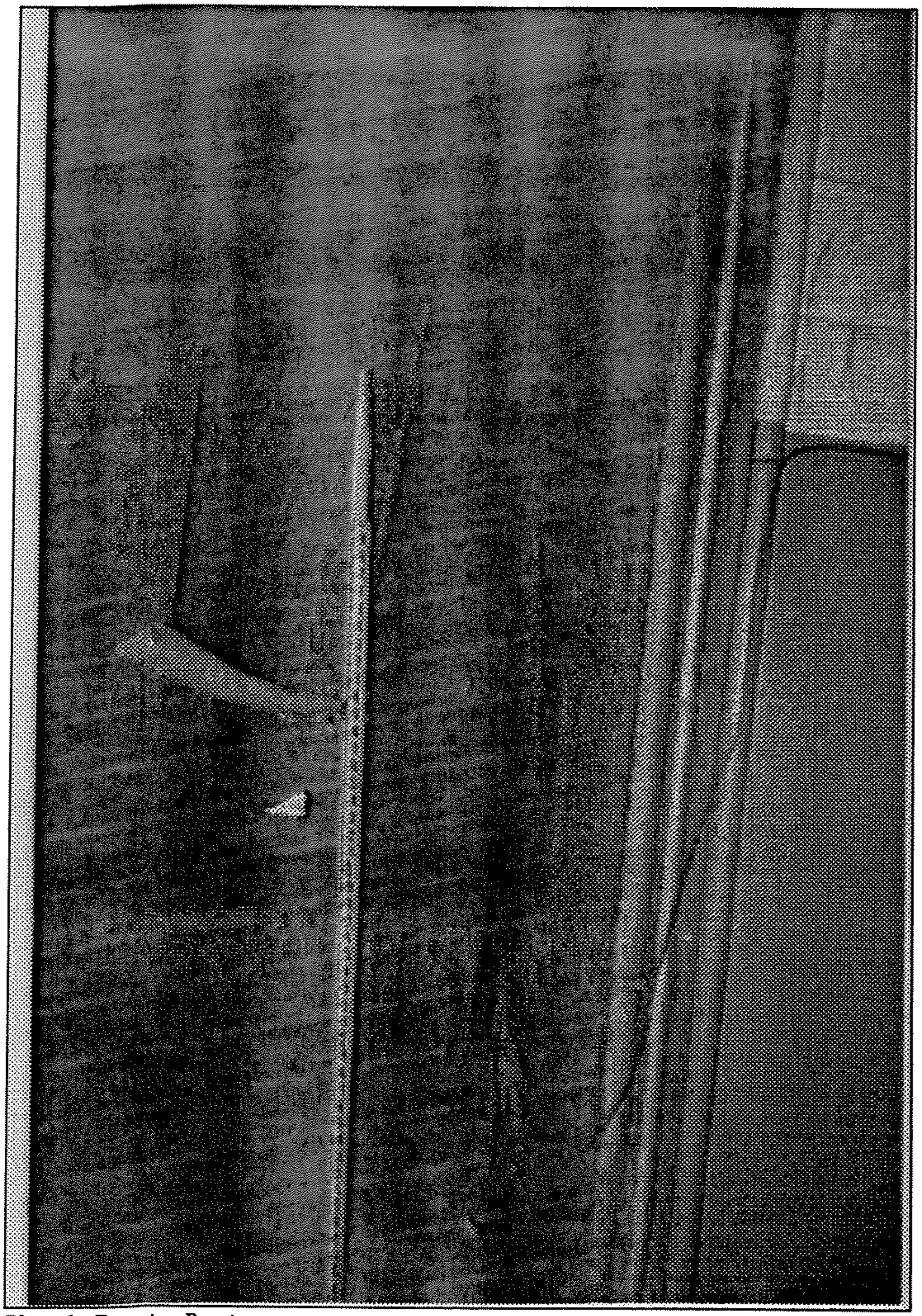

Photo 1. Trunnion Bearing.

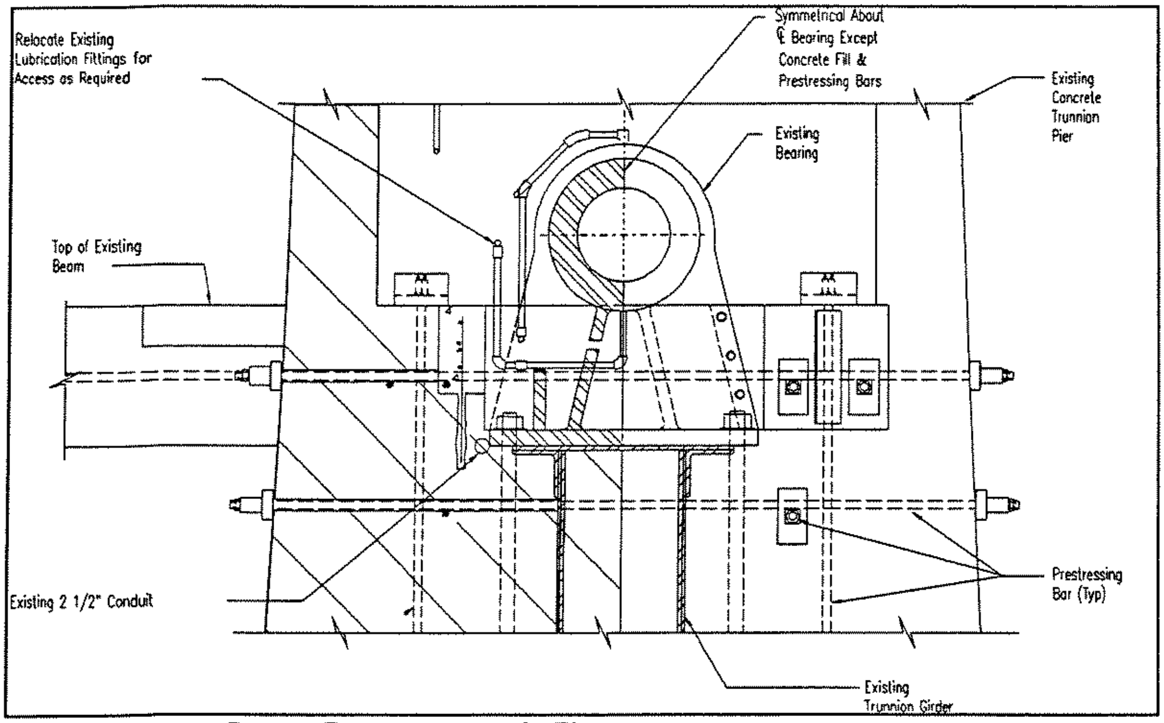

Figure 4. *Trunnion Bearing Encasement Retrofit, Elevation*

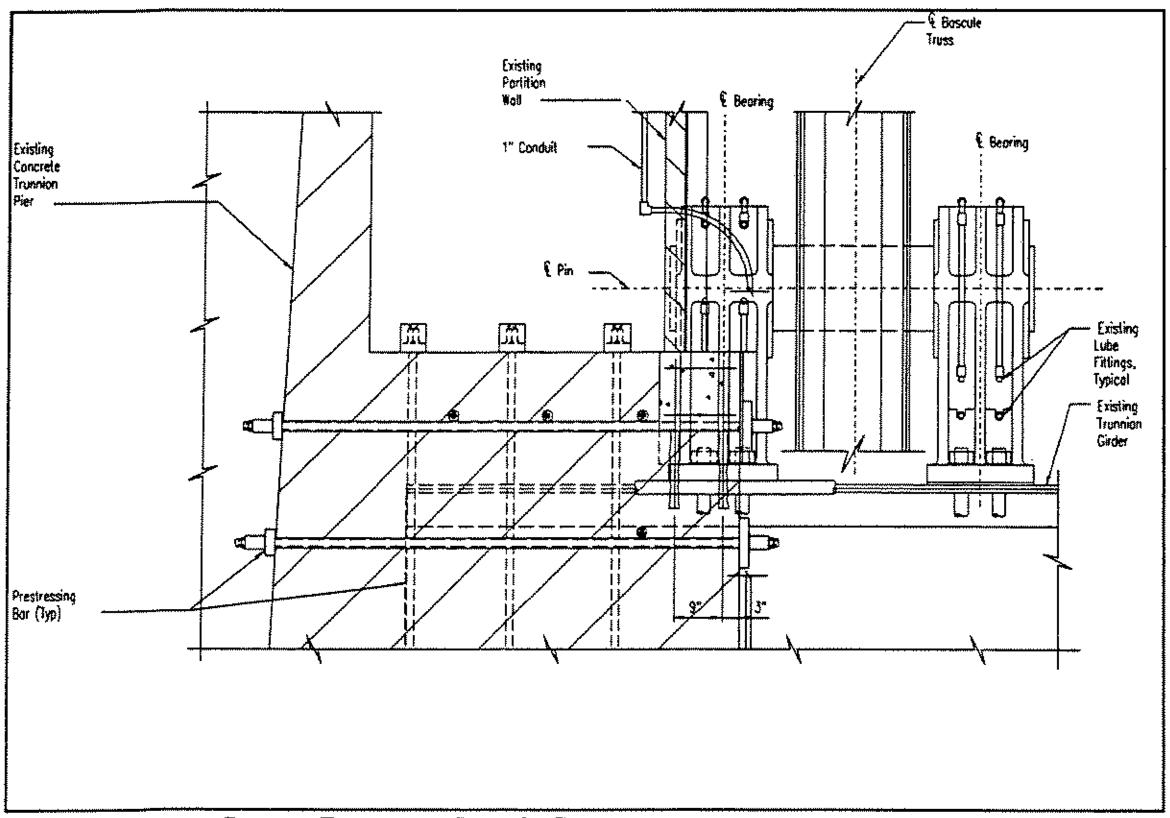

Figure 5. *Trunnion Bearing Encasement Retrofit, Section.*

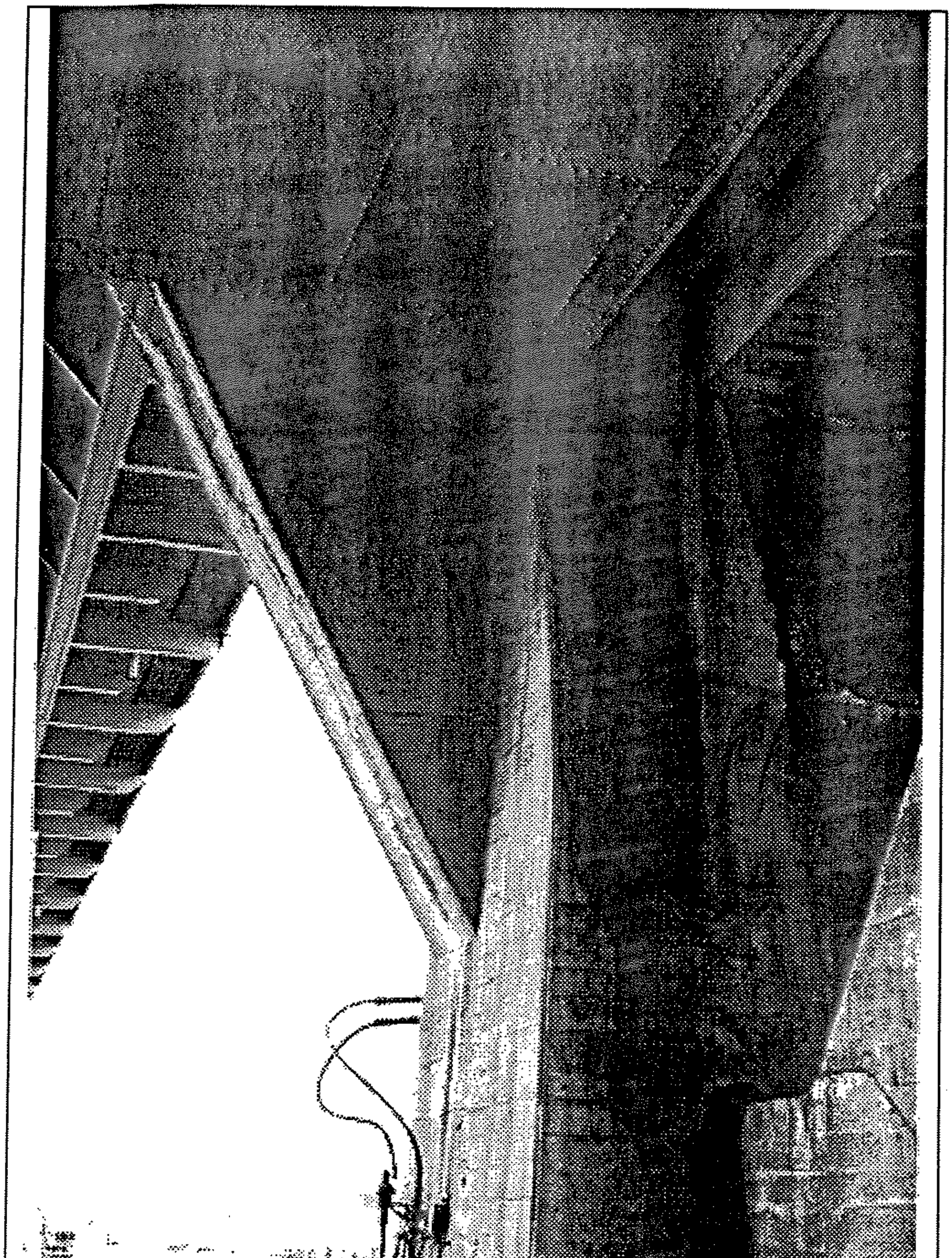

Photo 2. Counterweight box looking from below.

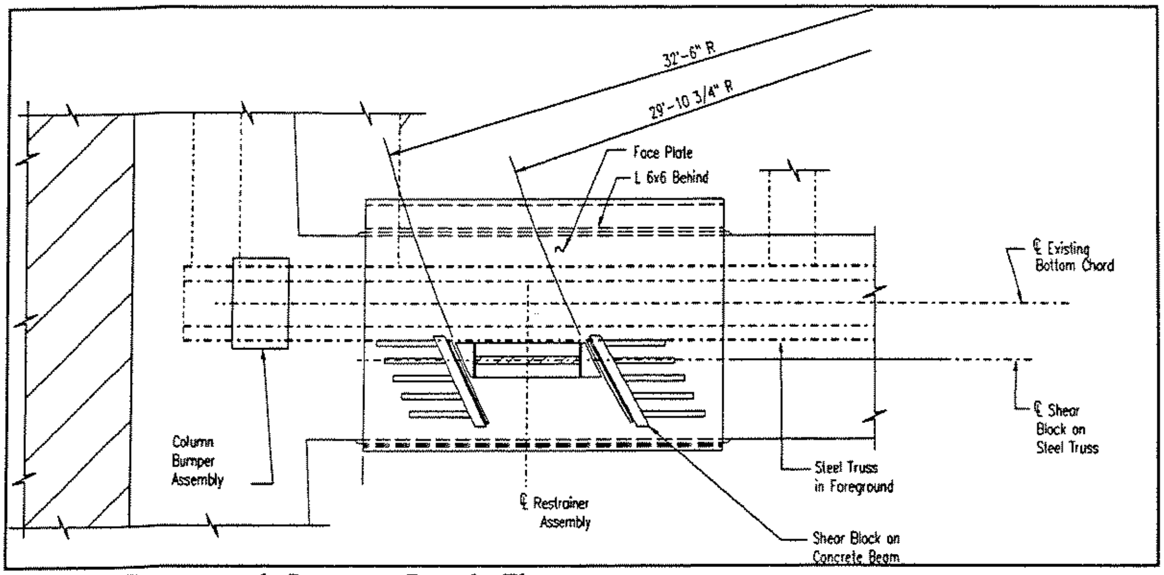

Figure 6. *Counterweight Restrainer Retrofit, Elevation.*

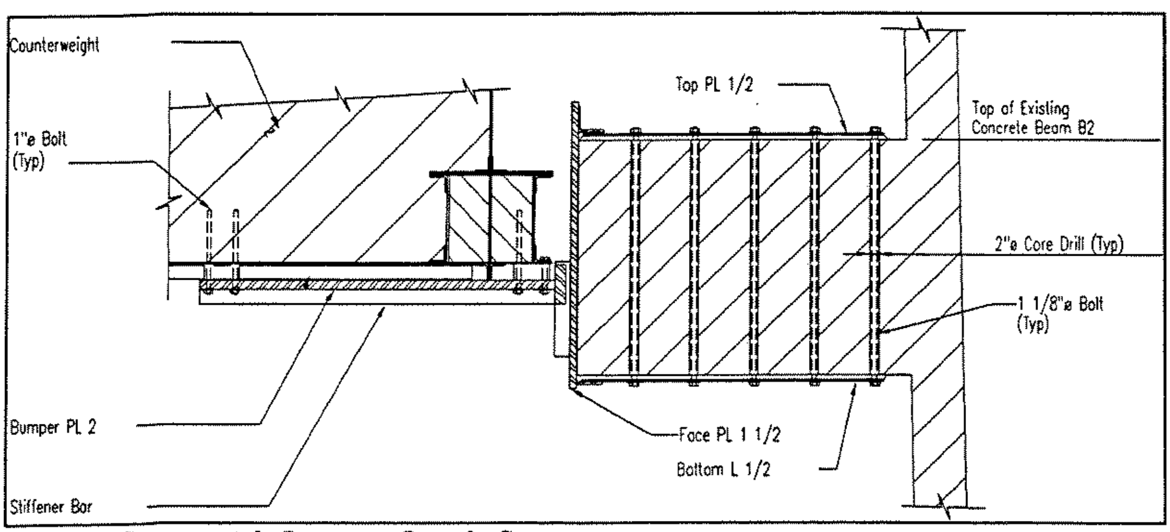

Figure 7. *Counterweight Restrainer Retrofit, Section.*

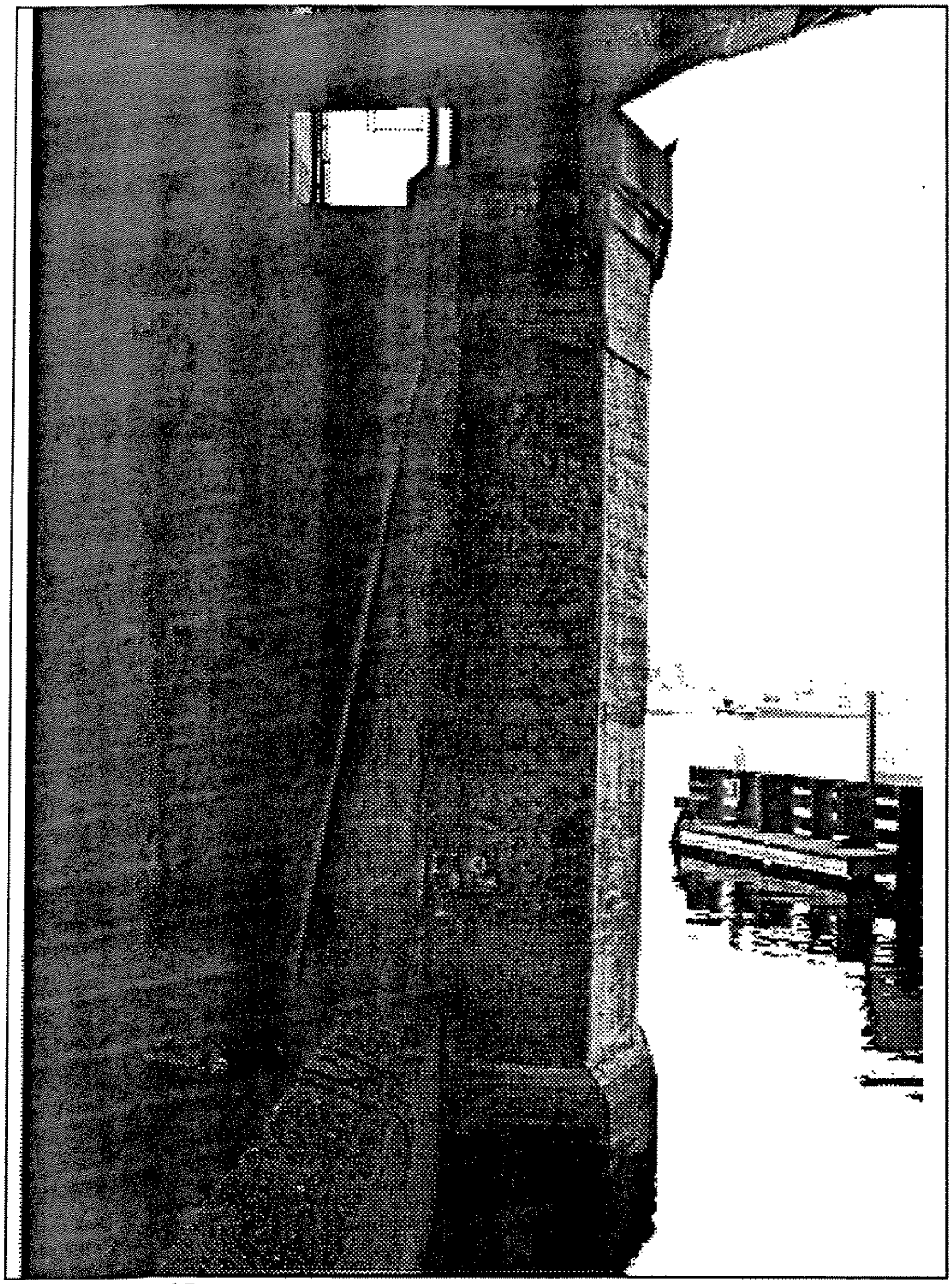

Photo 3. Channel Piers.

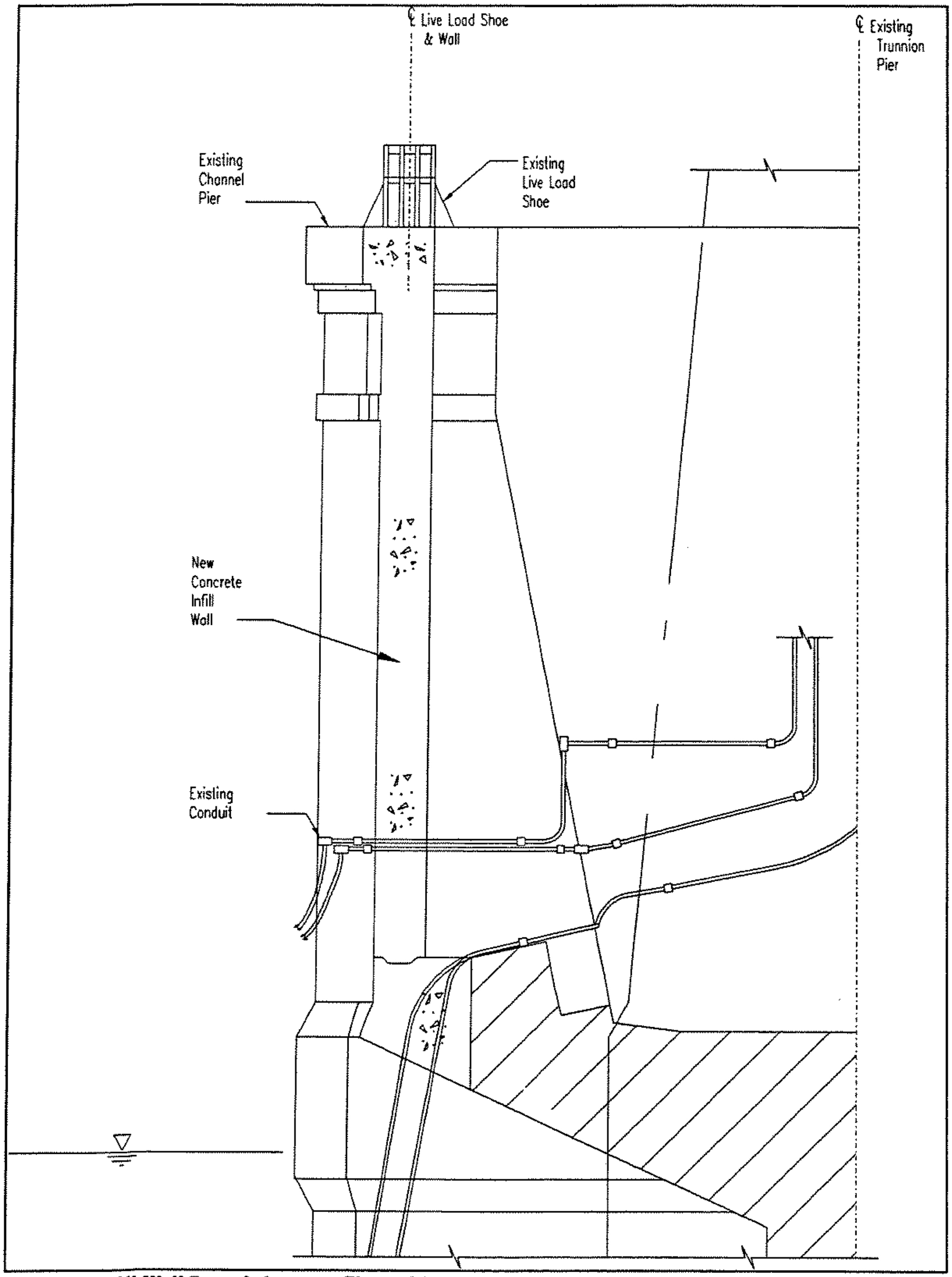

Figure 8. *Infill Wall Retrofit between Channel Piers.*

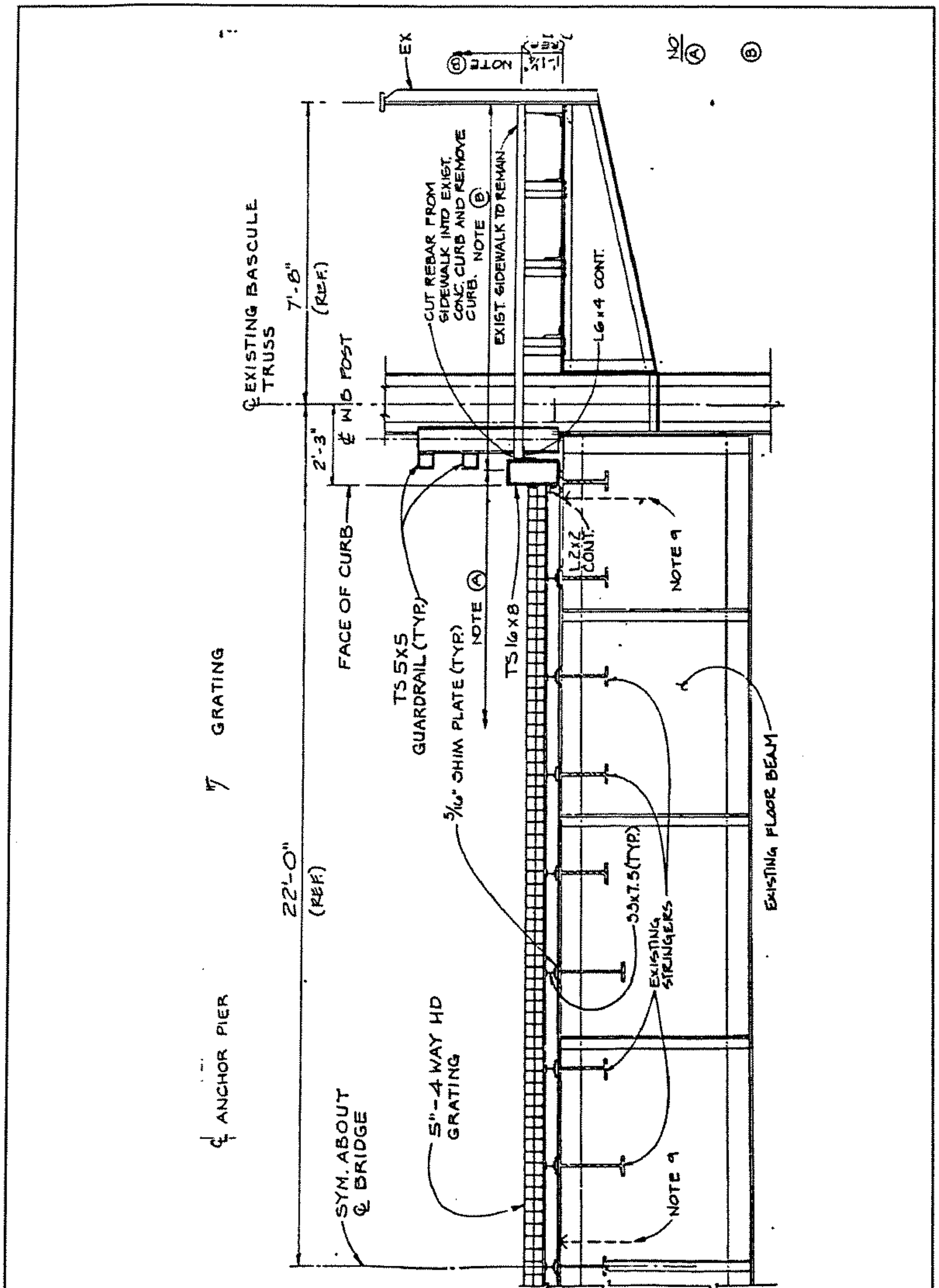

Figure 9. Deck Grating, Cross Section.

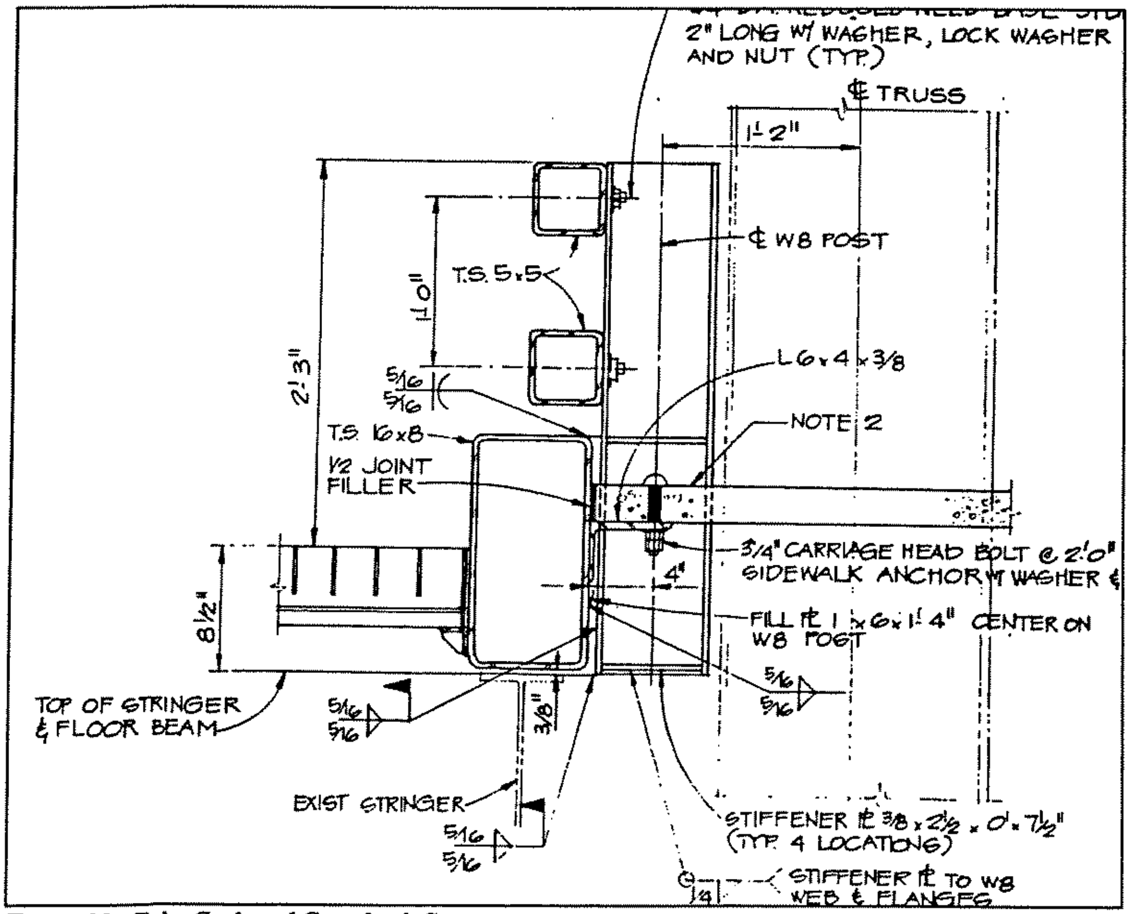

Figure 10. Tube Curb and Guardrail, Section.