HEAVY MOVABLE STRUCTURES, INC.

TWELFTH BIENNIAL SYMPOSIUM

November 3-6, 2008

Making Waddell Work in the 21st Century

Garry Tow, P.E.

William E. Nickoley, P.E.

Cristina Brosio, E.I.T.

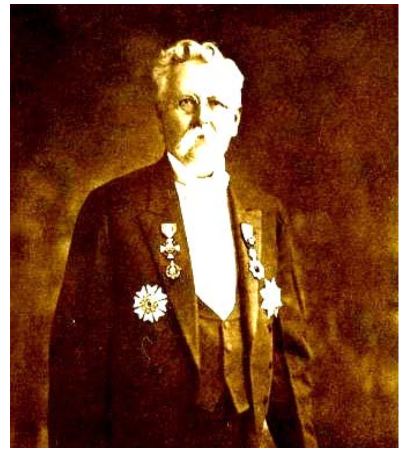
HNTB Corporation

212-594-9717

CARIBE ROYALE RESORT
ORLANDO, FLORIDA

Making Waddell Work in the 21st Century

By Garry Tow, P.E. , William E. Nickoley, P.E., and Cristina Brosio, E.I.T.
HNTB Corporation
5 Penn Plaza
New York, NY 10001
212-594-9717
(212-947-4056 Fax)



Dr. J.A.L. Waddell

Portsmouth Memorial Bridge as it now exists, view from Portsmouth, NH to Kittery, ME
US Route 1 over the Piscataqua River

ABSTRACT

John Alexander Low Waddell (1854–1938) was a prolific bridge designer, having more than one thousand structures to his credit in the U.S., Canada, and overseas. In movable bridge circles, he is known as the "Father of the Modern Vertical Lift Bridge."

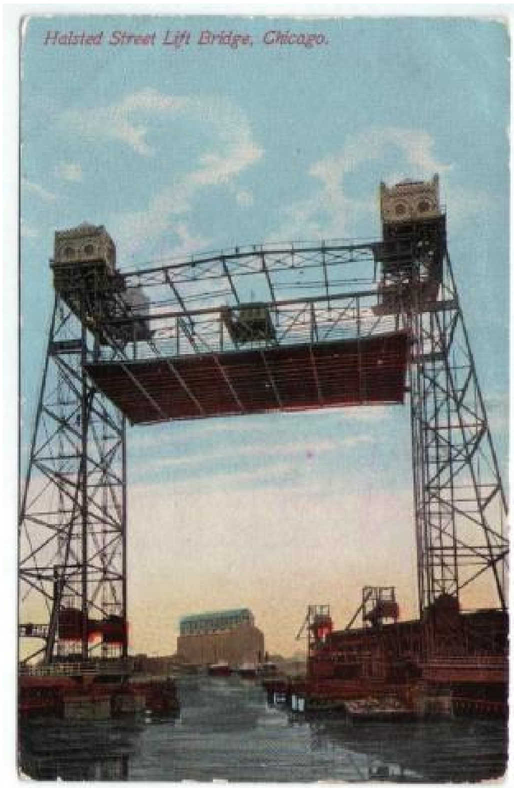
This paper will discuss the design for rehabilitation of Waddell's Portsmouth Memorial Bridge. The bridge was constructed in 1922, and is primarily comprised of three 300 foot truss spans. The center truss span is a span-drive vertical lift span with a vertical clearance of 150 feet at full lift. The bridge lifts approximately 4000 to 4500 times per year and is jointly owned by the New Hampshire and Maine Departments of Transportation. The bridge will be rehabilitated for a projected 50 years additional life.

Initial structural inspection and rating of the structure revealed excessive deterioration and weakening of the roadway framing, lower truss panel point connections, and truss lower chords. Mechanical inspection of the trunnions, sheaves, equalizers, and counterweight ropes resulted in concern about overstress conditions, and fatigue life of the trunnions. However, a focus on minimizing impacts to the historic downtown Portsmouth area, and sensitivity to archaeological and historic resources in the area including the bridge itself, led to the decision to rehabilitate and upgrade rather than replace the structure.

The design schedule was fast-tracked between January and November, 2007, during which time balance had to be maintained regarding: (1) the desired optimum restoration of original appearance; (2) minimum disruption during construction; and (3) the need to upgrade the original design to current AASHTO standards.

The design, therefore, features rehabilitated and upgraded existing towers to support the larger sheaves necessary for a heavier lift span and counterweight; larger operating machinery; and a new lift span to be floated in during a short navigational shutdown. We believe that, had he been available for the task, Mr. Waddell would have enjoyed the challenge associated with addressing needed changes to his original design -- just as we did.

I. J.A.L. Waddell's Legacy



Waddell's South Halsted Street Bridge of 1894.

Dr. John Alexander Low Waddell (1854–1938) was a prolific bridge designer, having more than one thousand structures to his credit in the U.S., Canada, and overseas. In movable bridge circles, he is known as the "Father of the Modern Vertical Lift Bridge." Having this title, he established many of the guidelines and concepts used to design these structures, as well as the operating systems for them. Dr. Waddell is also renowned for placing his concepts and other ideas in books, papers, periodicals, and addresses on the subjects of bridge design – and promotion of the engineering profession and its standards, in general.

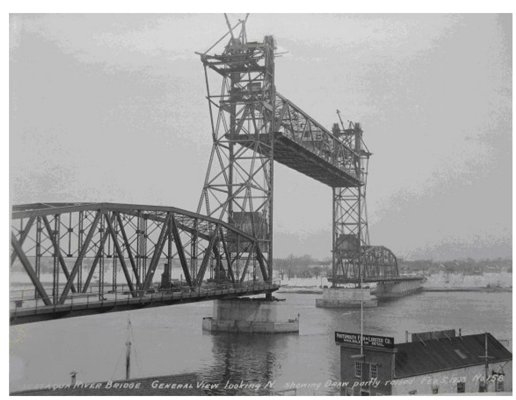
The modern vertical lift bridge is usually traced to the South Halsted Street design prepared for the Sanitary District of Chicago, built in 1893 just short of Waddell's 40th birthday. Although this design was a breakthrough, Dr. Waddell had to wait 15 years, well into his fifth decade, before another one of his vertical lift bridge designs was accepted and built.

Span drive vertical lift bridges have been around since 1908. Waddell and his partner from 1907-1914, John Lyle Harrington, received a patent together for the span drive concept in that year, when the first span drive vertical lift bridge was built in Keithsburg, IL.

Shortly after Harrington's departure (to found what has now become HNTB Corporation, at that point), Dr. Waddell completed his two volume textbook, *Bridge Engineering.* This classic includes over 260 pages of specifications for bridge design and construction. The influence of these specifications can still be seen in current AASHTO and AREMA specification documents today.

II. The Original Portsmouth Memorial Bridge Design

Three separate structures completed in 1922 carry U.S. Route 1 across the Piscataqua River: the Portsmouth/Scott Avenue Approach Spans, the Memorial Bridge, and the Kittery Approach Spans. The Memorial Bridge is the focus of this paper, consisting of three steel truss spans of nearly 300 feet each -- the vertical lift span over the channel, plus two flanking tower spans.



Portsmouth Memorial Bridge during construction in 1922.

The center span of the Memorial Bridge is a span drive vertical lift of the type patented by Waddell and Harrington. Steel truss lift towers, supported by each flanking fixed truss span, rise approximately 200 feet above the river. In the open position, the lift span provides 150 feet of vertical clearance for marine vessels within the 274 ft.-3 in. wide navigation channel. In the closed position, the span provides 21 feet of vertical clearance above mean high water.

Waddell's Portsmouth Memorial Bridge was designed using the span-drive concept, and in accordance with his 1916 specifications.

According to the original plans provided by NHDOT, supplemented by the description found in Hovey's book, *Movable Bridges*, original bridge loadings were as follows:

Classification	Structural Steel, Pounds	Machinery, Pounds	Machinery to Structural, Per Cent
One lift span	1,125,000		
Two towers	775,000		
Sheaves, trunnions, and bearings	....	100,000	5.26
Wire ropes and fittings	....	60,000	3.16
Equalizers	....	20,000	1.05
Operating machinery	....	60,000	3.16
Totals	1,900,000	240,000	12.63
Total machinery	240,000		
Grand total	2,160,000		

Using Waddell's specifications, the following would have been the basis of the design:

Lift Span Total Dead Load	1,710,000 lbs.
Live Load	equivalent to today's H-15
Impact Due to Live Load (highway traffic)	I = 100 / (nL + 200) = 28%
Impact Due to Live Load (electric railway)	I = 120 / (nL + 175) = 13%

Where:
n = clear width of roadway in feet / 20
L = length of span in feet

Wind Loads (towers)	15 psf horizontal with lift span in highest position
	30 psf horizontal with lift span in lowest position
Wind Loads (lift span)	300 lbs per lin. ft. on the empty span at level of the floor
Snow Load	50 pcf (assumed depth or weight not specified)

The following allowable stresses were used for medium and rivet carbon steels:

Tension on… net sections of all built members, and on net sections of flanges of all beams	16,000 psi
Bending on pins	27,000 psi
Bearing on pins	22,000 psi
Bearing on shop rivets	20,000 psi
Bearing on end stiffeners of plate girders (outstanding legs only)	16,000 psi
Shear on pins	15,000 psi
Shear on shop rivets	10,000 psi
Shear on plate girder webs, gross section	10,000 psi
Bearing on expansion rollers, lbs., d = diameter of the roller in inches	600*d*
For field rivets, the intensities for bearing and shear are to be reduced 20%.	
Turned bolts with driving fit are to be stressed the same as field rivets.	
Compression on struts with fixed ends, psi	16,000 – 60 *l/r*
Compression on struts with hinged ends, psi	16,000 – 80 *l/r*
Compression on gross section of flanges of rolled beams	16,000 psi
Compression on gross section of flanges of built beams, psi	16,000 - 200 *l/b*
Compression on forked ends, psi	10,000 – 300 *l/t*

In the above, *l* is the unsupported length of strut, flange, or jaw-plate in inches; *r* is the least radius of gyration of the strut in inches; *b* is the width of the flange in inches; and *t* is the thickness of jaw-plate in inches.

Waddell used nickel steel to improve the weight efficiency of his structures by means of the following allowable stresses:

Tension on… net sections of all built members, and on net sections of flanges of all beams	26,000 psi
Bending on pins	45,000 psi
Bearing on pins	35,000 psi
Bearing on shop rivets	30,000 psi
Bearing on end stiffeners of plate girders (outstanding legs only)	26,000 psi
Shear on pins	23,000 psi
Shear on shop rivets	14,000 psi
Shear on plate girder webs, gross section	16,000 psi
Bearing on expansion rollers, lbs., d = diameter of the roller in inches	900*d*
For field rivets, the intensities for bearing and shear are to be reduced 20%.	
Turned bolts with driving fit are to be stressed the same as field rivets.	
Compression on struts with fixed ends, psi	26,000 – 110 *l/r*
Compression on struts with hinged ends, psi	26,000 – 150 *l/r*
Compression on gross section of flanges of rolled beams	26,000 psi
Compression on gross section of flanges of built beams, psi	26,000 - 325 *l/b*
Compression on forked ends, psi	16,000 – 500 *l/t*

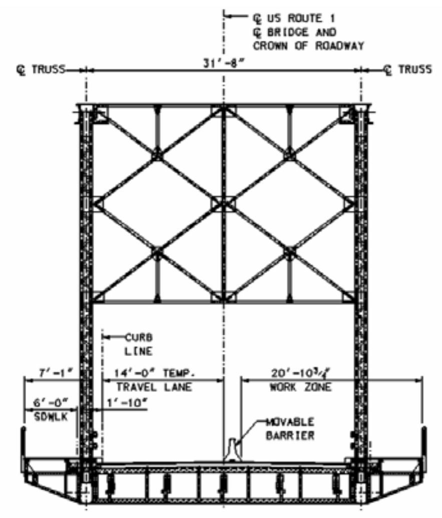
Per *Bridge Engineering,* Volume II, Chapter LXXVIII, Section 48 on page 1656, "All the preceding figures for both carbon steel and nickel steel are for total equivalent static loads without wind loads added; but when the latter are also included, the said figures in the designing of bridges proper are to be increased thirty (30) percent."

From the listing of the above allowable stresses, it would appear that deteriorated members from the original construction could be replaced essentially in-kind with today's ASTM structural materials. However, increased live loads associated with today's standards for traffic design result in increased dead loads, both of which preclude such an assumption. Also, today's economy demands the use of rolled shapes and welded members over the built-up riveted members of the past.

Portsmouth Memorial Bridge today, looking northwest toward Kittery, ME.

For the Portsmouth Memorial Bridge, the fixed trusses are variable depth with a maximum chord-to-chord dimension of 47 ft.-0 in. at midspan. Lift towers are supported by the fixed trusses at each channel pier, and extend 180 feet above the lower chord. The lift truss is constant depth with a chord-to-chord dimension of 35 ft.-0 in. The center to center truss dimension for all three truss spans is 31 ft.-8 in. The roadway width curb to curb is 28 ft.-0 in., carrying one lane in each direction. Six-foot-wide sidewalks are cantilevered outside of each truss line.

The roadway surface for the lift span was originally asphalt laid directly on 3 inch planks supported by transverse wooden ties on steel stringers, while the fixed spans were asphalt on reinforced concrete slabs.



TYPICAL FIXED TRUSS SPAN SECTION

The lift span roadway now consists of open steel grid decking, while the fixed span decks remain as designed. The roadway deck for the fixed truss spans is supported by transverse purlins, which are in turn supported by a framing system that is similar for the fixed and lift spans: stringers frame into floorbeams located at each truss panel point. The fixed truss span deck purlins consist of eleven, 7 in. deep, I-sections equally spaced between each truss panel point/floorbeam. Stringers for the lift span consist of seven I-shapes of varying depth equally spaced at 4'- 4", whereas stringers for the fixed spans consist of five I-shapes of varying depth equally spaced at 6'- 6". The variances in framing are representative of the original design loading which included both highway traffic and an electric trolley along the current southbound lane of roadway. Steel floorbeams for the three truss spans are 48 in. deep built–up I sections. The floorbeams are supported at each panel point along the lower chord of the trusses.

Sidewalk support is provided by cantilevered floorbeam brackets supporting two steel sidewalk stringers. The sidewalk consists of 2 1\2 in. thick timber planking supported on steel brackets and steel stringers.

Bearings for the truss spans include steel fixed bearings and roller expansion bearings. The fixed truss spans employ fixed bearings at the channel piers, and expansion bearings at the end piers. The vertical lift span is supported at the truss end panels with fixed and rocker expansion bearings.

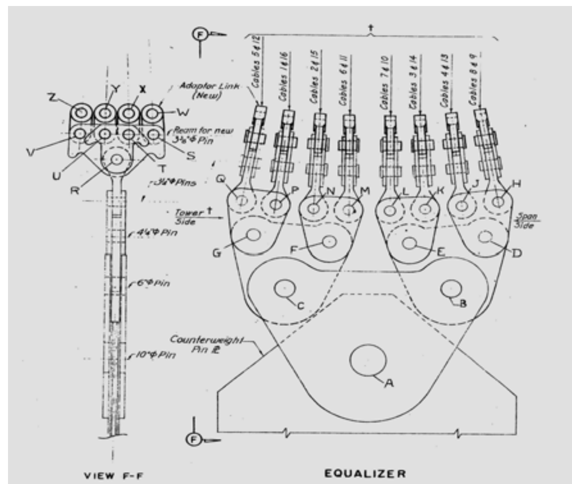
Substructures for the Memorial Bridge include two channel piers and two end piers. The end piers also serve as support for the Portsmouth and Kittery Approach structures. The channel and end piers are unreinforced concrete mass walls founded in rock. The channel piers are located in approximately 60 feet of water and measure roughly 85 feet tall from the top of foundation to the top of pier. The end piers are located in 10 to 15 feet of water and measure roughly 25 feet tall. Each pier is clad with masonry stone facing for a height of 15 feet centered about the high and low water elevations. A timber fender system is provided at each channel pier.

Nominal machinery allowable stresses in psi were also provided in Waddell's 1916 specifications, as follows:

Material	**Tension**	**Compression**	**Bending**	**Shear**	**Bearing**
Rivet Steel				5,000	10,000
Structural Steel	10,000	10,000 – 40 *l/r*	10,000	7,000	12,000
Forged Steel / Machinery Steel	12,000	10,000 – 40 *l/r*	12,000	9,000	15,000
Cast Steel	8,000	10,000 – 40 *l/r*	8,000	6,000	10,000

Once again, although the allowable stresses shown appear to be well within range of common materials used today, heavier traffic loads the consensus of experience reflected in today's specifications preclude replacement of machinery in the same envelope.

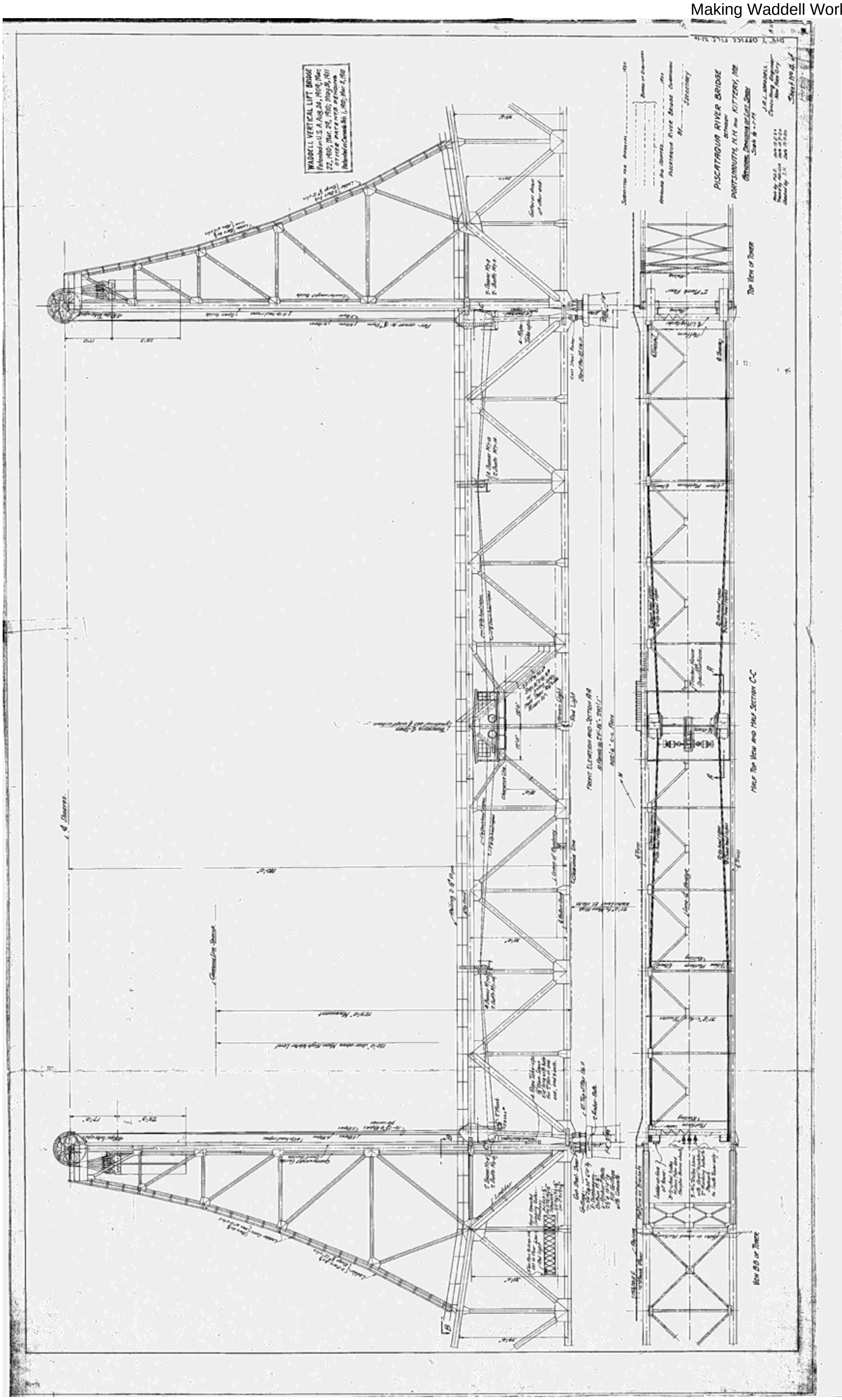
Currently, four 10'-6" diameter counterweight sheaves on top of the two towers each support 16 counterweight ropes of 1-5/8 inch diameter. This is a 77:1 ratio of the sheave diameter to the rope diameter, although Waddell allowed a minimum 60:1 ratio of diameters of tower sheaves to their ropes in his 1916 specification, and could have gone as small as 97.5" under that guideline. Also, although Waddell had specified Plow Steel for all ropes in 1916, Improved Plow Steel ropes were provided in 1922. One end of the counterweight ropes is connected to take-up adjustment mechanisms on the span and the other ends are connected to equalizer mechanisms at their respective counterweights. The counterweight sheaves are supported on large trunnion shafts straddle mounted in bronze bushed pillow block bearings.



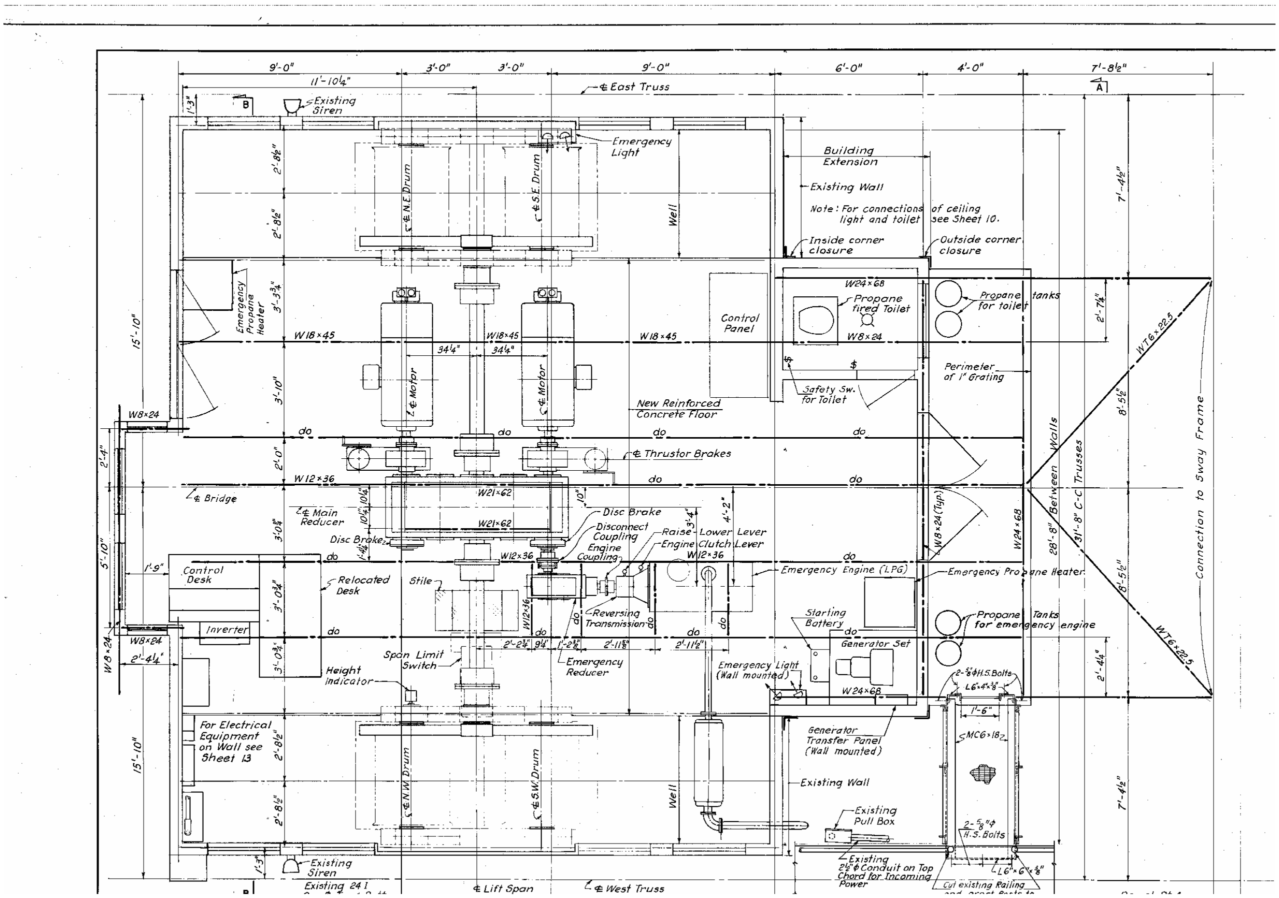
Existing counterweight sheave assembly at left. Below the sheaves, as shown at right, the equalizer system connects ropes to counterweight using 55 separate pin connections.

The existing vertical lift bridge is span driven, with the driving machinery located on the movable span. Two 100 horsepower, 580 rpm, electric motors and brakes were originally connected to a central gear frame, along with solenoid actuated spring-set brakes. Thruster brakes were provided in place of these in 1975. Two sets of operating drums are still driven by the central machinery, although the original gear frame has been replaced by a central speed reducer. Each of the 4 drums pays out and reels in two pairs of 1 inch diameter operating ropes to raise and lower the span. Original drum diameter of 36 inches is slightly smaller than the 40:1 minimum basic requirement of Waddell's 1916 specification, as is the diameter of deflector sheaves at the ends of the lift span.

The existing arrangement of the lift span is shown on the next page., followed by the current drive machinery arrangement in the existing combination machinery / control house.



Current configuration of the Portsmouth Memorial Bridge, as designed by J.A.L Waddell.



Existing configuration of operating machinery in combination machinery / control house at center of span, as modified during the 1975 rehabilitation. Extensions of house to the right and left (toward the south and north ends of the span, respectively) were added to better accommodate the needs of the operator, including toilet facilities. The operator controls the span from the control desk at left.

The bridge electrical control system currently uses relay logic to control the span while raising and lowering. The wound rotor span motors are controlled by means of Thyristor drives. Automatic gate control equipment is located in the control house, and manual gate controls are located in the operator booths located on each approach. A radio control system incorporating a PLC (Programmable Logic Controller) system is used to control actions between the control house and traffic control equipment.

III. The Need for Change

Over the decades, the need to carry larger and heavier traffic and new understandings concerning design requirements needed to withstand the resulting loadings first led to modifications to Waddell's original design, and has now required total review and re-design of the structure and operating systems.

Previous changes included the following:

- After only a few years, the sheaves on the north tower were reportedly replaced in the 1930's, followed by the sheaves on the south tower in the 1940's. The SW inboard bushing was replaced as part of the 1982 rehabilitation.

- Counterweight ropes were replaced, along with take-ups, in 1961. An adaptor link was added to the rope connections at each set of equalizers at that time, as well.
- The plank and asphalt floor of the lift span was replaced with 5" open grid in 1947. This exposed the floor framing and associated portions of the superstructure to runoff from above. Numerous repairs were made over the years since that time.
- A new operator house was provided in 1975. The central gear frame was also replaced with a large speed reducer that year, along with new motors and thruster-actuated brakes of the same nominal ratings – although the way motors were rated had changed during the 1950's and 1960's. The original manual emergency capstan arrangement was replaced with a liquid propane gas engine and emergency disc brakes at the same time.

The overall deterioration of the various existing systems became more of a concern as the 21st Century arrived.

- Structural inspection and rating of the structure in 2003 revealed excessive deterioration and weakening of the roadway framing, the lower truss panel point connections, and truss lower chords. The structural inspection resulted in the lift span being immediately posted for 9 tons, and an emergency repair project was initiated in 2004 to address the most severely deteriorated areas and bring the rating back up to 20 tons.

Deterioration in lift span floor framing.

Counterweight rope equalizers. Inset shows worn connection at lower pin.

- Mechanical inspection and analysis of the trunnions, sheaves, equalizers, and counterweight ropes resulted in concern about overstress conditions, and the fatigue life remaining in the trunnions. Ratings performed concerning the trunnions revealed that they did not meet current standards for design, and that they were at the end of their useful life due to fatigue considerations. Equalizer pin connections exhibited clearances of up to ¾ inch. And counterweight ropes were found to be worn and deteriorated, particularly at the tangent points with the sheaves. On this basis, inspection of these mechanical components was mandated on a six month basis until rehabilitation or replacement would occur. The wire ropes were found to be deteriorating and wearing at a high rate during these inspections, to the extent that an emergency repair contract was performed in during April, 2008. It was also determined during the inspection and rating that the lift span had increased in weight from 1,710 kips in 1922, to 1,849 kips in 2004.

- The relay-based electrical system was showing its age, having been last replaced in 1975. Remaining from the original Waddell design are vertical trolley conductors to bring in the 480 volt, 3 phase, power. These exposed conductors must be consciously avoided by maintenance personnel as they perform their work.

At left: Exposed vertical electrical power conductors and trolleys. Counterweight ropes are visible on the right of the photo.

- The operator station still remains in the machinery house, as reconstructed in 1975, and this results in several disadvantages.
  - The operator cannot easily leave the control house if the span is raised. This could leave the operator stranded should there be a malfunction.
  - Operator visibility of the sidewalks and roadway is only fair in this location. Because of this, several video cameras with monitors above the control console are used to supplement visibility. Also, gate tenders with radios are currently stationed on each approach.
  - The operator environment within the machinery room, with machinery located between the operator control station and the restroom facilities, is not desirable. Also, the existing restroom facility does not have a water and sewer connection due to its location on the moving span, requiring periodic pump out in addition to water delivery.

Combination machinery / control house on the existing lift span. Approach and base of tower are seen at left.

IV. Study of Alternatives

A study of alternatives was performed by HNTB in 2004 to address the deficiencies found during the inspection. It was evident that a major rehabilitation or replacement of the structure would be necessary. Alternatives included:

- limited rehabilitation of the existing lift span and approaches,
- restoration and upgrading of the Memorial Bridge to either HS-20 or HS-25, and
- replacement of the existing structure with either a new vertical lift bridge, a new bascule bridge, or a tunnel beneath the river.

For a description of this study and its various alternatives, see *Planning the Portsmouth Memorial Bridge Rehabilitation* by William Nickoley, PE, as presented at the 11th Biennial Heavy Movable Structures Symposium in 2006.

Rehabilitation of the existing structure and upgrading it to HS-20 was selected by the Client. This upgrade would include replacing the existing lift span entirely, while rehabilitating and upgrading the tower spans and providing improvements to the operators as well as the public.

A focus on minimizing impacts to the historic downtown Portsmouth area, and sensitivity to archaeological and historic resources in the area including the bridge itself, led to the decision to rehabilitate and upgrade rather than replace the structure.

V. Challenges During the New Design

A. Structural

Per the Design Criteria established at the beginning of the project, the capacity of the structure is being improved to HS-20, with maximum improvement in roadway safety features. Since the Memorial Bridge is currently eligible for listing on the National Register of Historic Places, the appearance of the structure is to remain essentially unchanged.

Based on the conditions found during inspection and existing ratings, the Lift Span will be replaced while the Tower Approach Spans 1 and 3 will be rehabilitated and upgraded.

Two views of new control house, to be located on the south (Portsmouth) approach.

The existing operator controls at the center of the lift span, now within the same room as the span drive machinery, will be removed to a new control house located on the south tower. This new control house will provide improved visibility to the extent possible, better accessibility and possibility of operator evacuation should a malfunction occur with the span raised, plus improved operating environment, including water and sewer service.

The new lift span has been designed by HNTB per AASHTO LRFD. Substantially-in-kind replacement of the Lift Span was mandated since it is a historical structure, but agreements were made with SHPO to retain the existing overall truss profile while only replicating existing built-up, latticed members, including truss verticals, diagonals, sway bracing, and upper laterals. The existing lift span will be matched as closely as possible with the bridge designed by Dr. Waddell, while modernizing the structure with 21st century materials, design specifications and technology. This will provide an upgraded structure that also preserves the historic aesthetic of the Memorial Bridge for many years to come.

View between the trusses of the new lift span, as designed, showing box and H-shape truss members emulating appearance of built up members on existing span. Note new machinery house above new filled grid roadway.

A Warren-type through truss of the same length is maintained by the new design, having verticals and parallel chords at 35'-0" between centerlines of chords, with 10 panels spaced at 29'-8½". Chords will now be of modern welded closed box shapes, diagonals will be built-up box sections with perforated top and bottom flanges to simulate the original lacing bars and, similarly, verticals will be built-up H-shaped sections with perforated web plates instead of lacing bars. Upper lateral bracing will maintain the existing X-bracing system with built-up I-shaped sections, using cut-out web plates with depth to match top chord. Lower lateral bracing and K-bracing connections from truss panel points to midspan of each intermediate floorbeam are to be made of WT steel sections. The lifting girder is to be a deep welded plate girder with cutouts in web at midspan to replicate existing lifting girder basic configuration, but with ends of solid web plates to accommodate lifting rope connections. Perforated plates will simulate lacing in various locations without the labor cost associated with replacing existing lacing in kind.

For sidewalks, composite lumber decking was chosen, having a finished texture, size and look to match the existing 3" X 8"wood planks. These will provide a lower maintenance cost and longer life, while keeping the wood plank-like feel and appearance of existing sidewalks

Since the floor system will be hidden by the closed deck, and aesthetic preservation is less of a concern, some changes were made to the existing roadway support system to improve details and to lighten the structure. The quantity of roadway stringers was reduced from 7 to 5 to match fixed truss span stringer spacing of 6'-6". These roadway stringers will be made composite with the concrete in a partially-filled grid deck to reduce stringer weight and depth, and will be made continuous and placed on elastomeric bearings on top of floorbeam top flanges to reduce stringer weight and depth. This also eliminates shear connections to the floorbeam webs rather than replicating the existing simple stringers framing between floorbeam webs. The elastomeric bearings will control the transfer of longitudinal and transverse forces to the floorbeams and the lateral bracing system. The floorbeam depth has been reduced to match lower chord depth, thereby utilizing details that allow for a full moment connection of floorbeams to chords

A partially filled concrete grid deck will be used on the lift span instead of existing open grid deck. This will provide better rideability, an increase in bike safety, and better protection of structural elements under roadway. The heavy deterioration of the existing roadway framing members and lower truss connections governed the replacement of the existing lift span. However, a partially filled grid deck is 3 to 4 times heavier than the existing open grid deck, and therefore requires additional counterweight to balance it.

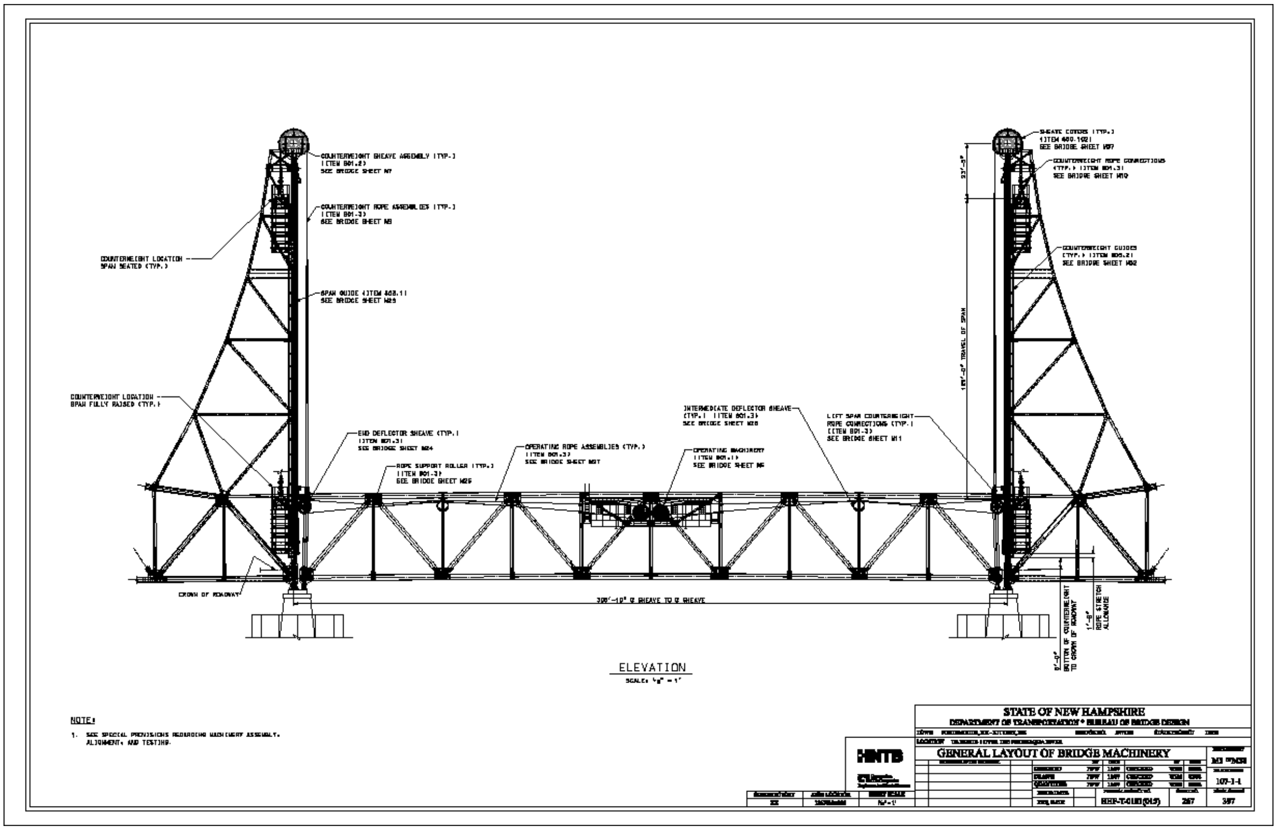
Deck replacement for the fixed truss spans will involve removing the existing deck which has a parabolic cross-slope supported by roadway purlins spanning transversely 2'-5" on center. Because of its short span, the existing deck is currently a 5¼" concrete slab reinforced with two layers of welded wire fabric and covered by 2" of overlay. However, working with the existing truss geometry, the design of the new deck with a 2% cross slope is controlled by the existing distance between top of floorbeams and bottom of sway frames.

Current NHDOT standards suggest using an 8" minimum concrete slab with a minimum clear distance from the bottom of the slab to the lower reinforcing of 1¼" and a minimum of 1" between layers of reinforcing. When an overlay is used (typical thickness of 2⅝"), the clear distance from the top of the concrete slab to the top reinforcement must be greater than 2½". For a bare concrete deck, NHDOT has suggested an additional ½" of sacrificial concrete, bringing the top cover distance 3", in order to provide greater protection for the upper mat of reinforcement. The 3" top cover can be accommodated by adding ½" to the deck, making it a 8½" concrete slab, or by bringing the top layer of reinforcement down by ½" and keeping the 8" overall depth. The intent is to maintain the existing elevation of the roadway at the curb line, facilitating the transition of the new deck to the existing deck on the Kittery Approach Spans. Increasing the overall depth of the deck would then mean having to raise the curb line and in turn the entire roadway profile, unacceptably reducing the existing vertical clearance over the roadway. Therefore, the roadway purlins will be removed, and an 8" deck with 3" of top cover and the minimum acceptable distance between reinforcement layers of 1" will span 6'-6" between stringers.

The new deck spans the stringer spacing with minimum slab thickness and minimum reinforcing steel. This new deck system is considerably stronger than the existing concrete deck, not only because of the increased slab thickness and greater amounts of reinforcement, but also because the deck is being made composite with the existing stringers, strengthening the entire deck framing system.

It was necessary to make local retrofits and repairs to various truss members of the flanking spans for increased live load demand, and to strengthen the towers for larger dead load of the lift span. Flange plates were added to the truss verticals, and web plates were added to the truss diagonals. The front tower legs were strengthened by adding additional web plates. Bracing members remain unchanged in the retrofit. The height of the tower was increased by 6 feet in order to accommodate changes to the counterweight and current AASHTO requirements for counterweight ropes concerning maximum deviations from vertical. An added benefit of this additional height is increased access for inspection of both the uphaul ropes and the counterweight ropes.

The weight of the counterweight was increased in order to accommodate the additional dead load of the lift span by increasing its height by a little more than 3 feet. Rope attachments are now made directly to a lifting girder rather than to the existing equalizer assemblies. This is a much simpler system, minimizing almost all the maintenance now associated with the existing equalizer pins, a nearly futile endeavor due to their inaccessible location and lack of grease fittings.



New general arrangement of lift span and machinery. Note large machinery house. Control house, located beneath tower on south (Portsmouth) approach, is not shown.

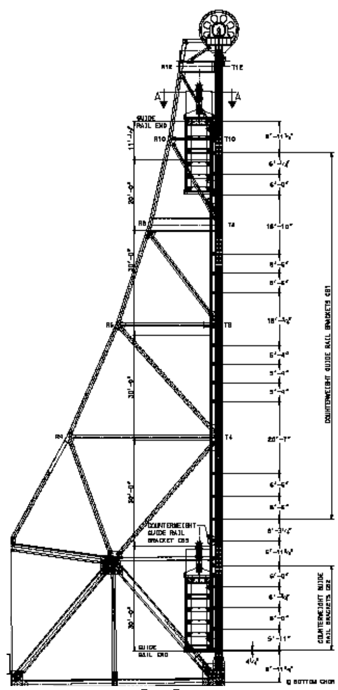
B. Mechanical

Replacement of the operating machinery and electrical system is required due to the replacement of the lift span, but larger equipment is also necessary due to the increased dead load of the lift span increasing and to meet today's standards for design. Replacement of the counterweight ropes, sheaves, and trunnion assemblies is required for the same reasons, in addition to their having reached the end of their useful life.

The new lift span's dead load is being increased to 2,500 kips due to the partially filled grid deck and to the HS-20 and HL-93 capacity upgrades required for the structural design. Because the new lift span and tower span will be essentially the same configuration, every step of the mechanical design was a challenge due to space limitations:

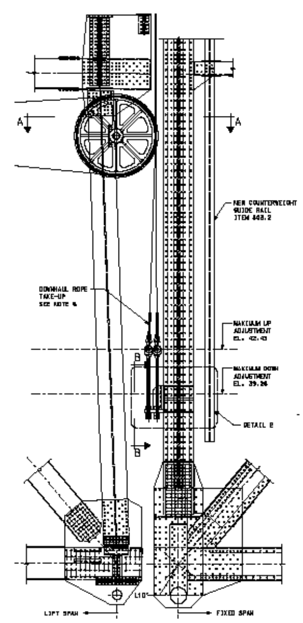
- Eighty counterweight ropes of 1.875 inch diameter are now required to replace 64 ropes of 1.625 inch diameter. This, in turn, requires that the new counterweight sheaves be at least 135 inches diameter rather than the existing 126 inches diameter, with the consequence that the lifting girder on the new lift span be 4.5 inches further forward from the sheave trunnions, and the counterweight must be 4.5 inches further back on each tower. In addition, because current AASHTO requirements would not allow the existing equalizers to be duplicated due to 1:30 maximum deviation of the counterweight ropes from a vertical plane in the longitudinal direction from their tangent point with the sheave, the existing counterweight attachment method was not possible. A lifting girder was added to the counterweight, and the top of the tower had to be raised by approximately 6 feet to accommodate the new arrangement.

- In order to minimize the mechanical power required, antifriction bearings are now being used to support the new counterweight sheave trunnion bearings. This limits the new requirements to two 125 horsepower motors, but these are still larger than the two existing 100 horsepower motors.
- The new operating machinery will be significantly larger than that existing, requiring a larger machinery house even though the operator station is being removed to a new operator house.
- The existing 36 inch diameter drums and deflector sheaves for 1 inch diameter operating ropes were smaller than that allowed by Waddell's 1916 specification initially. The new operating ropes are 1.5 inch diameter, and the new drums and deflector sheaves are 72 inches in diameter following current AASHTO requirements.
- Because of the larger deflector sheave diameter required, the location of the existing deflector sheaves was no longer possible due to space considerations. The existing deflector sheaves were located between the flanges of the end vertical of the existing lift span truss. Being twice the size, the new deflector sheaves had to be located either above the top chord, necessitating redirection of the operating ropes halfway between the machinery house and the end of the span; or else they needed to be located completely inside the vertical members at the end of the truss. By providing adequate protection against trucks that might be leaning to the right, beyond the theoretical traffic envelope, this preferable design was utilized.

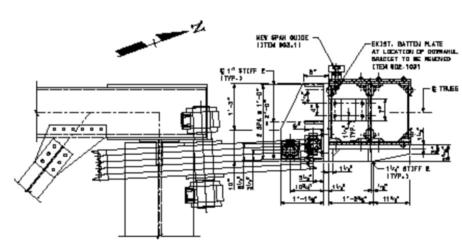


top extended to accommodate tangent angle of larger ropes with larger sheave.

Inspection platform below sheave improves access for inspection and maintenance of counterweight and operating ropes.



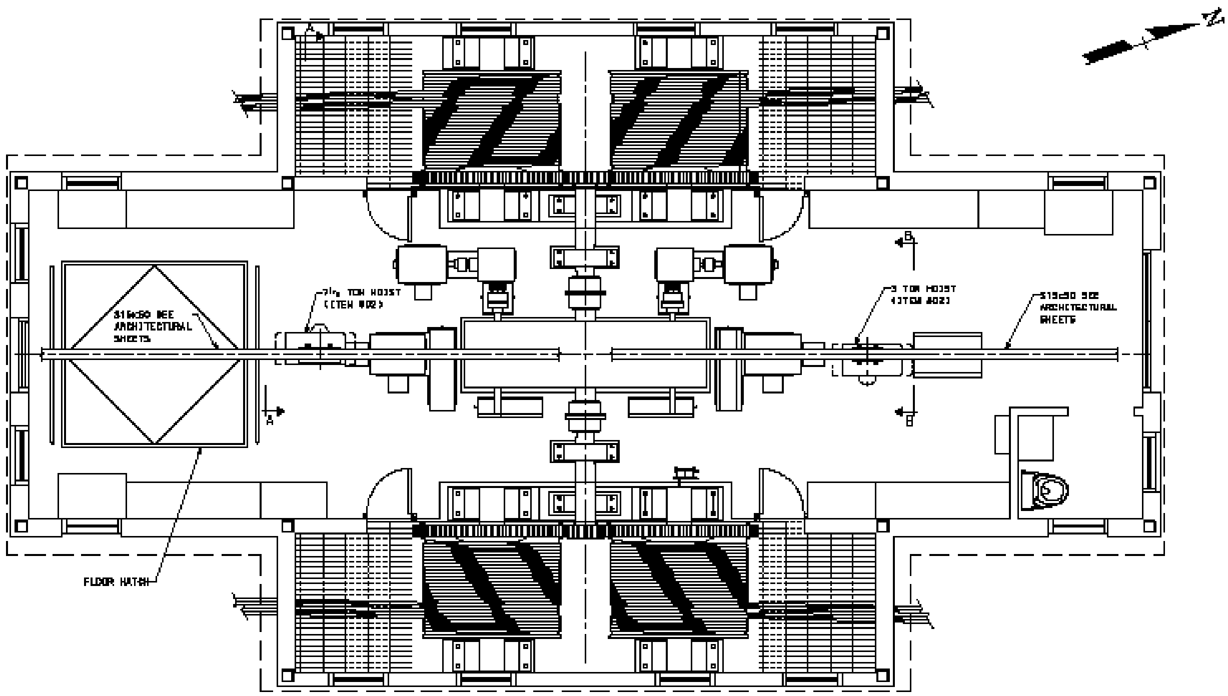
DETAIL 1



VIEW A-A

Above and below at right, deflector sheaves had to be relocated to the inside of the truss at each corner of the lift span in the new design because of their larger size.

- Span and counterweight guides utilize UHMW plastic wear pads on stainless steel rails to eliminate the need for lubrication.
- As with the original design, no auxiliary counterweights will be provided to compensate for the counterweight ropes even though the lift of the span is over 100 feet. This also adds to the machinery size and capacity required, but facilitates seating of the bridge while precluding the need to add span locks.



Machinery arrangement in machinery house on new lift span, showing the larger capacity machinery within redesigned machinery house. Note ease of access, plus service cranes provided, for maintenance and repair of the machinery and electrical systems.

C. Electrical

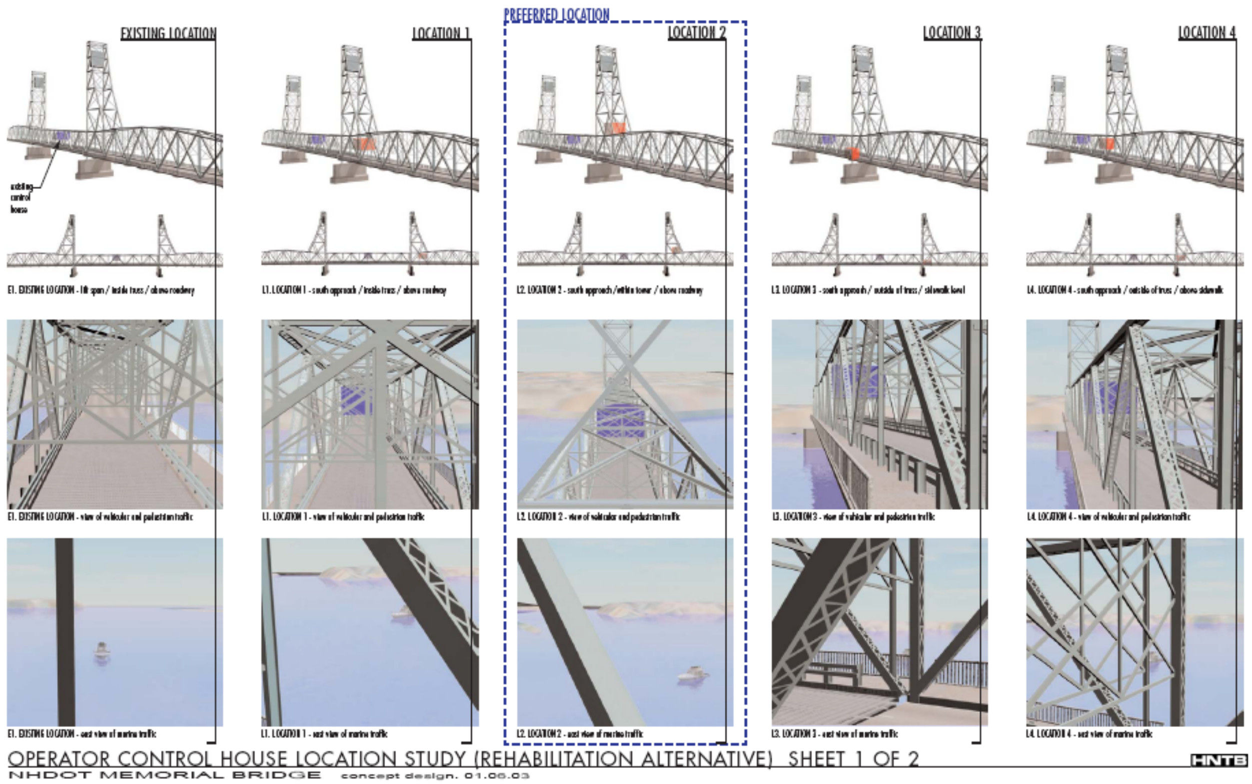
The new electrical system will be PLC based and will use droop cables of both copper strand and fiber optic construction to transfer power and control circuits, respectively. The existing bare wires and trolleys for power pickup will therefore be eliminated. PLC control of flux vector drives will provide smooth state-of-the-art operation.

With reference to his 1916 specifications, Dr. Waddell embraced the electrical technology of his day along with that currently available for structural and mechanical. It is not a stretch to believe he would probably have embraced today's electrical technology, as well.

D. Architectural

The operator of the lift span has been stationed in the machinery house since original construction. The machinery house reconstruction of 1975 finally provided indoor toilet facilities, but running water and sewer remained unavailable at this location. Also, should the lift span ever cease operation in an intermediate position, the operator has the potential of being stranded on the partially raised lift span.

During the Study of Alternatives, HNTB architects performed an analysis using 3-D modeling to determine the best alternative location on the Portsmouth approach for a new control house, in terms of visibility. Ability to see the navigation channel, the roadway, and the sidewalks were considered, along with the portion of the tower that would afford the simplest structural support.



A Study of Alternatives was performed for optimum placement of the control house, for the best visibility of both the roadway and the channel.

The new control house will be located behind the path of the counterweight, just above the top chord of the new lift span. This will remove the bridge operator from the noise of the machinery, place the operator closer to parking, provide a roomier location with comfort facilities, kitchen, and locker space, along with additional storage areas.

VI. Conclusion

The Portsmouth Memorial Bridge is an excellent example of Dr. J.A.L. Waddell's work. Many of his pioneering concepts continue to be the standard in vertical lift bridge design and construction, and the flavor of his 1916 specifications for movable bridge design and construction remains in much of both the AASHTO and AREMA specifications for movable bridges.

The rehabilitation of an 85 year old movable bridge designed using Waddell's specifications is challenging mainly because times have changed regarding heavier trucks, materials available, and a changed economy of construction.