New Hampshire Division of Historical Resources

Determination of Eligibility (DOE)

Inventory #: DOV0158

DOE Review Date: 1/27/2006 ***Date Received:*** 9/26/2018

☑ Final DOE Approved
MR

Property Name: **General Sullivan Bridge**

Area: Newington-Dover Project Area (ND)

Address: Spaulding Turnpike over Little Bay

Town: Dover **County:** Strafford

Reviewed For: R&C

DOE Program(s):
Federal Highway, NH Dept. of Transportatio

DETERMINATION OF ELIGIBILITY

National Register eligible, individu
State Register eligible, individually

Integrity: Yes **Level:** National

Criteria: ***A:*** Yes ***B:*** ***C:*** Yes ***D:*** ***E:***

STATEMENT OF SIGNIFICANCE:

10/10/2018: Inventory form was updated to include a discussion on the bridge's integrity since it was first evaluated in 2006 as well as a comparative analysis of remaining bridges of similar design and engineering firm. The bridge remains eligibile for listing in the National Register of Historic Places on a national level for its history and engineering significance.
The DHR disagrees with the proposed boundary which should include the entire resource (counting the modern elements as not historic).

Period of Significance: 1934 to 1968

☐ Period not applicable

AREAS OF SIGNIFICANCE(S)

Engineering
Transportation

Boundary: footprint of bridge, abutments and approaches

Follow Up:

Notify appropriate parties.

Comments:

INDIVIDUAL INVENTORY FORM

NHDHR INVENTORY # DOV0158

Name, Location, Ownership

1. Historic name: General Sullivan Bridge
2. District or area: N/A
3. Street and number: Route 16 (Spaulding Turnpike)/ Route 4 over Little Bay
4. City or town: Newington and Dover
5. County: Strafford and Rockingham
6. Current owner: State of NH

Function or Use

7. Current use(s): Transportation: Pedestrian-related
8. Historic use(s): Transportation: Road-related

Architectural Information

9. Style: N/A
10. Architect/builder: Engineer: Fay, Spofford & Thorndike/ Contractor: Lackawanna Steel Construction Co. (superstructure); Crandall Engineering (substructure)
11. Source: various (see 2004 form)
12. Construction date: 1934
13. Source: various (see 2004 form)
14. Alterations, with dates: (since 2004) 2011: north approach and abutment reconstructed, south approach removed; 2010: pedestrian fence added
15. Moved? no ☒ yes ☐ date:

Exterior Features

16. Foundation: Concrete
17. Cladding: N/A
18. Roof material: N/A
19. Chimney material: N/A
20. Type of roof: N/A
21. Chimney location: N/A
22. Number of stories: N/A
23. Entry location: N/A
24. Windows: N/A
    Replacement? no ☐ yes ☐ date:

Site Features

25. Setting: Suburban neighborhood; Waterfront
26. Outbuildings: N/A
27. Landscape features: Little Bay
28. Acreage: 0.68 acres

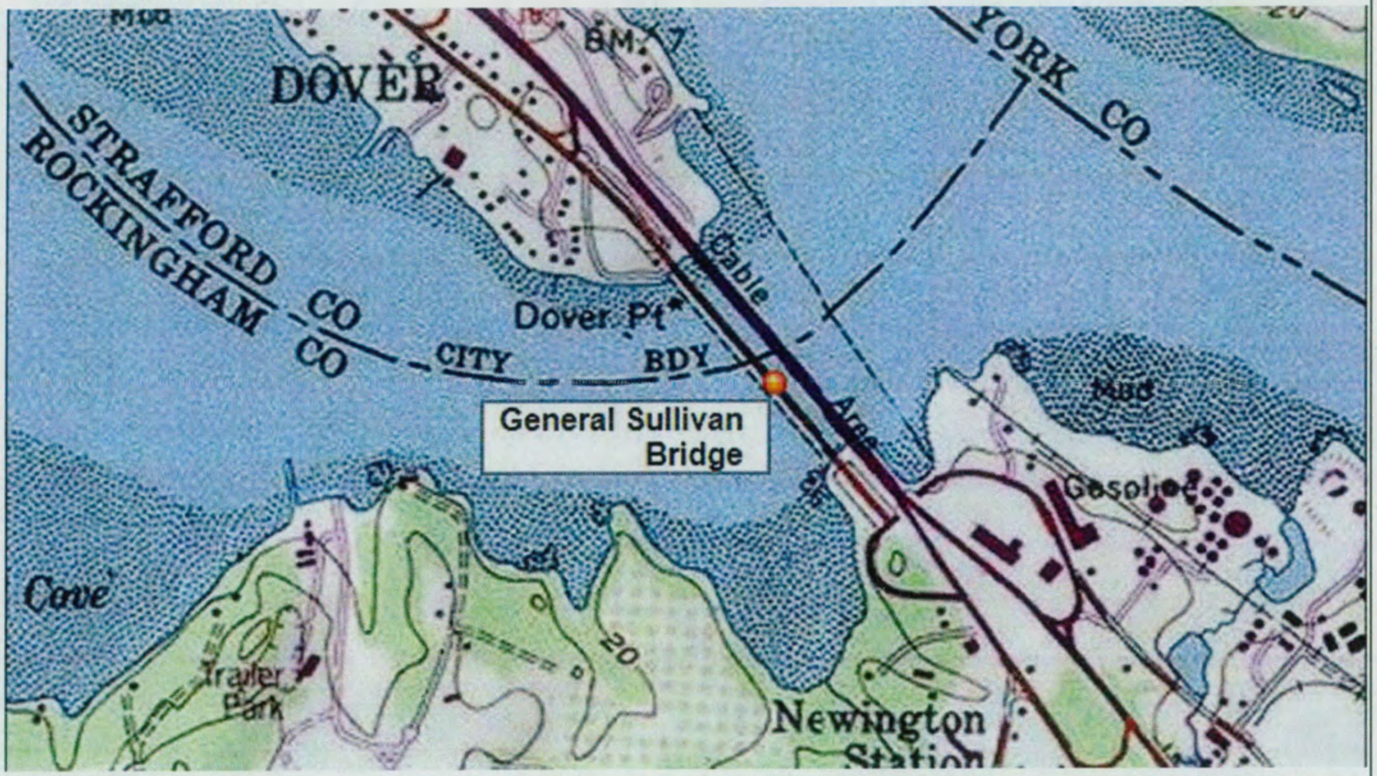
35. Photo #1 Direction: SE
36. Date: July 2018
37. Reference (file name or frame#): DOV0158_1

29. Tax map/parcel #: N/A
30. State Plane Feet (NAD83): X: 1,208,717.2 KP
    Y: 226,286.7
31. USGS quadrangle and scale: Portsmouth 1:24,000

Form prepared by

32. Name: Nicole Benjamin-Ma
33. Organization: VHB
34. Date of survey: July 2018

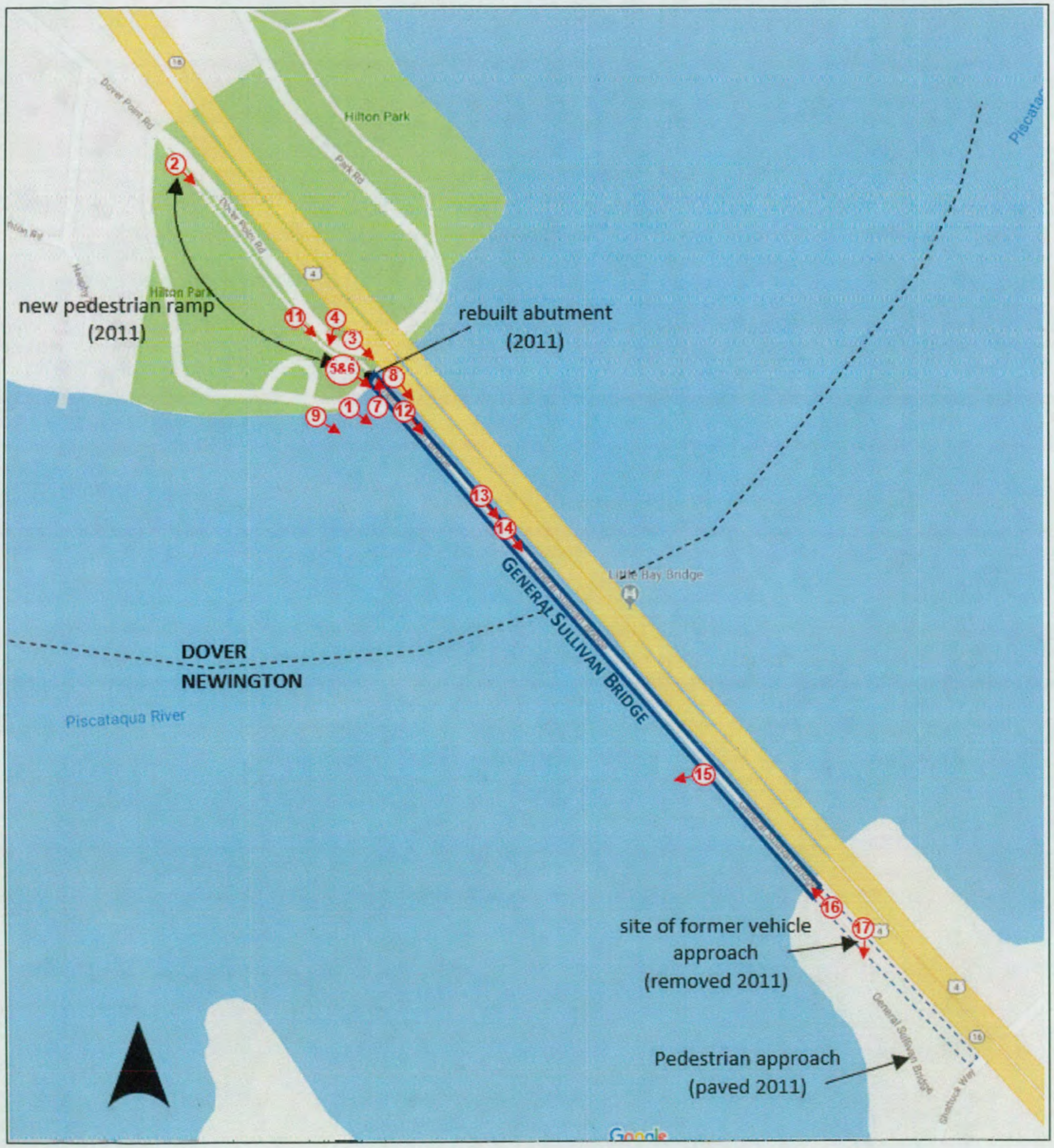
39. LOCATION MAP:



40. PROPERTY MAP:

(see next page)

40. PROPERTY MAP:



41. Historical Background and Role in the Town or City's Development:

(updated August 2018)

The 2004 inventory form details the history and significance of three other Fay, Spofford & Thorndike (FST) bridge designs, which with the General Sullivan Bridge, advanced the design of, and encouraged the nation-wide adoption of, long-span continuous truss bridges. These include the Lake Champlain Bridge carrying NY Route 185 and VT Route 17 between Crown Point, NY and Chimney Point, VT (designed 1927), the Sagamore Bridge carrying MA Route 6 over the Cape Cod Canal in Sagamore, MA (completed 1935), and the Bourne Bridge carrying MA Route 28 across the Cape Cod Canal in Bourne, MA (completed 1935) – the latter two are often referred to as the "Cape Cod Canal bridges." All four bridges exhibit the distinctive and aesthically-pleasing composition of a center arched through truss with deck side trusses. Changes have been made to these bridges since the 2004 inventory form. The Lake Champlain Bridge was demolished in 2009 and replaced with a network tied arch design, which visually references the center through truss design of the earlier bridge. The Cape Cod Canal bridges are still in service, with minor recent alterations related to maintenance, such as roadway deck replacement.

The 2004 form briefly discusses some additional early, 1920s highway continuous bridge designs, including two examples from Portland, OR, and two Midwest examples from Missouri and Illinois. The two Portland bridges – the Ross Island Bridge and the Sellwood Bridge – were designed by Gustav Lindenthal to span the Willamette River, and opened in 1927. The Ross Island Bridge is a cantilevered deck truss bridge of continuous design; the roadway deck and railings were recently replaced and the bridge is extant. The Sellwood Bridge had a main span comprising a four-span continuous Warren deck truss, and was replaced in 2016. The old US 36 Missouri River Bridge carried US 36 between St. Joseph, MO, and Elmwood, KS, and was a continuous through truss bridge completed in 1929 by the firm of Sverdrup and Parcel. It was replaced in 1984. In 1930, the Strauss Engineering Company completed the Quincy Memorial Bridge, carrying US 24 over the Mississippi River in Quincy, IL. An evaluation is underway for the potential replacement of this bridge.

43. Architectural Description and Comparative Evaluation:

(updated August 2018)

Alterations since 2004:

As part of the construction of the new Little Bay Bridge, the north and south approaches to the adjacent General Sullivan Bridge were re-routed in 2011. Now often referred to collectively as the Little Bay Bridges, this set of two bridges currently carries the Spaulding Turnpike (Route 16) over the Little Bay, bypassing the General Sullivan Bridge. As noted in the 2004 inventory form, by the 1960s, increased traffic necessitated the construction of the Eastern Turnpike Bridge, which carried southbound turnpike traffic while the General Sullivan Bridge continued to carry northbound traffic. In the 1980s, a second bridge was constructed directly adjacent to the Eastern Turnpike Bridge to carry the northbound traffic, known as the Capt. John Rowe Bridge. Together, the twin bridges carried traffic in both directions, bypassing the General Sullivan Bridge completely for automobile transportation. By the early 1990s, the General Sullivan Bridge was in use as a dedicated crossing for pedestrians and bicycle traffic.

Increasing traffic demands resulted in alterations to the Little Bay crossing once again beginning in 2011, when construction started on a new Little Bay Bridge. Built between the Eastern Turnpike Bridge and the General Sullivan Bridge, the new bridge carries southbound traffic, while the rehabilitated older bridges together carry northbound traffic. To facilitate the construction of the north roadway approach of the adjacent Little Bay Bridge, the north approach to the General Sullivan Bridge was rerouted, and a new pedestrian/bike support structure was constructed to connect the General Sullivan Bridge to Hilton Park and Dover Point Road/Hilton Drive (Photos 2-7, 11).

The new structure begins approximately 155 feet northwest of the bridge, and consists of two sections. The structure begins on the west side of Dover Point Road/Hilton Drive as an elevated ramp, supported on retained fill with a three-sided mechanically stabilized earth (MSE) wall with precast panel facing designed to look like stone blocks (Photos 3 and 11). A 3.5-foot-high metal post railing lines both sides of the ramp. At the south end of the MSE wall portion, a two-span, continuous I-girder bridge ties into the deck of the General Sullivan Bridge (Photos 3-5, 7). The recent bridge structure follows a curved, serpentine shape on the horizontal plane to meet the earlier bridge deck. It is supported on piers comprising single-drilled shafts and cast-in-place reinforced caps (see attached plans, Figures 1-4).

The concrete wingwall and approach embankment on the north side of the General Sullivan Bridge were removed, exposing the back of the original north bridge abutment, which was nearly entirely reconstructed (Photos 6-7). As described in the 2009 inventory form update, the original abutment was a closed end, bin type abutment, consisting of concrete walls that create a container into which fill is added. As part of the 2011 project, the abutment was reconstructed on the original seat and footing (Photo 7). The front of the concrete seat was refaced, and the wingwalls removed. The new abutment is a stub abutment on a spread footing, rising approximately 2.5 to 4 feet above the footing (the shorter height reflecting the water side). It serves as an open end abutment, as it is does not retain an embankment or fill behind it. It is somewhat unconventional, as the 2011 pedestrian/bike support structure and the General Sullivan Bridge meet at the abutment, meaning the abutment shares some characteristics with a wall-type pier as well.

Although no reconstruction occurred at the south end of the General Sullivan Bridge, the vehicular approach leading northwest towards the bridge from Shattuck Way was removed. A paved curvilinear path was added southwest of the former approach, to serve pedestrians and bicycles between Shattuck Way and the bridge.

The general condition of the bridge has declined since 2004. Detailed inspections of the bridge determined it was in critical condition, and the exterior portions of the deck exhibit advanced deterioration. In 2015, chain link fencing was added to the center of the bridge along the entire length, as a safety measure to keep pedestrians away from the outside deck extremes (Photos 12-13, 16). Truss members exhibit section loss, pack rust, and corrosion holes, and the underwater piers have damage from sulfates and were in need of repointing (VHB and HDR for NHDOT 2017: 3).

Comparable Properties:

The 2004 inventory form noted that the identification of directly comparable bridges within NH is problematic, as there were no other long-span continuous truss bridges built during this era. Based purely on bridge length, the form noted that only four extant bridges (as of 2004) were longer than the General Sullivan Bridge: the Sarah Mildred Long Bridge, carrying the Route 1 Bypass over the Piscataqua River between Portsmouth, NH, and Kittery, ME (1940); the Piscataqua River Bridge, carrying I-95 over the Piscataqua River between Portsmouth and Kittery (1971); the 1966 Eastern Turnpike Bridge; and the 1984 Capt. John Rowe Bridge. Since the 2004 form, the Sarah Mildred Long Bridge closed in 2016 and was replaced in 2018, and the Eastern Turnpike Bridge and Capt. John Rowe Bridge were heavily rehabilitated as the northbound Little Bay Bridge and reopened in 2017.

Other comparable bridges mentioned in the 2004 inventory form were the three earlier FST bridges (see update to #41. Historical Background and Role in the Town or City's Development, above), and a 2005 historic context for the General Sullivan Bridge groups these four FST bridge designs as defining the early development period for continuous truss highway bridge design in the United States (Casella 2005: 2). During this early period, between 1927 and 1937, these canonical four bridges proved the feasibility and potential economy of continuous truss design, influencing its use throughout the 20th century. It should be noted that an additional example of a continuous truss bridge, also utilizing an arched main span with flanking suspended deck spans, was later constructed in Amesbury and Newburyport, MA, just 25 miles south of the General Sullivan Bridge. Carrying 1-95 over the Merrimack River at a comparably wide crossing at 1,346 feet, the John Greenleaf Whittier Bridge ("Whittier Bridge") was designed by the Massachusetts Department of Public Works and constructed in 1951. Although built outside of the early development period for continuous truss design, the bridge is noted as being based on the Bourne Bridge and Sagamore Bridges over the Cape Cod Canal, with the three main span lengths measuring exactly half that of the earlier canal bridges. The historic bridge inventory form for the bridge suggests that the adaptation resulted in "visual awkwardness," lacking the aesthetic impact of the canal bridges (S.J. Roper and MassDOT, AME.927/NWB.930, 1990). The Whittier Bridge was replaced in 2016.

44. National or State Register Criteria Statement of Significance:

(updated August 2018)

A 2005 determination of eligibility (DOE) by DHR, finalized in 2006, determined the property eligible for the National Register under Criteria A and C at the state level; the 2004 inventory form also argues that the bridge conveys national significance under Criterion C as an early and highly-influential example of continuous truss highway design in the United States. The General Sullivan Bridge retains its historic significance, and this significance has been enhanced by the subsequent loss of comparable bridges, namely the Lake Champlain Bridge (Crown Point, NY and Chimney Point, VT), the Sarah Mildred Long Bridge (Portsmouth, NH and Kittery, ME), the Sellwood Bridge (Portland, OR), the US 36 Missouri River Bridge (St. Joseph, MO and Elmwood, KS), and the potential looming replacement of the Quincy Memorial Bridge (Quincy, IL).

45. Period of Significance:

(updated August 2018)

The previous DOE used a period of significance of 1934 to 1955, reflecting the date of construction through the 50-year cutoff date. The ending date of the period of significance should be updated to 1968, reflecting the current 50-year cutoff date.

46. Statement of Integrity:

(updated August 2018)

Despite the 2011 replacement of the north approach and abutment to the bridge from Dover, and the adjacent construction of the Little Bay Bridge, the General Sullivan Bridge retains a high degree of integrity, comparable to the level discussed in the 2004 form and 2005-2006 DOEs. The losses of the south vehicular approach, north approach, and north abutment impacted two contributing features of the historic structure; however, as the engineering significance of the bridge is associated with its overall continuous truss design, the signature engineering and aesthetic features remain intact. Subsequent deterioration has affected the physical historic integrity of the bridge, but the historically significant features of the structure are still evident. Thus, the bridge retains a high degree of integrity of location, design, materials, workmanship, feeling, and association.

The addition of the Little Bay Bridge in 2011 directly adjacent to the General Sullivan Bridge has affected the setting of the bridge, impeding viewsheds to and from the bridge on the east side. However, the setting on the west side of the bridge, overlooking the Little Bay, Dover Point, and Hilton Park, is largely intact, so while the integrity of setting has been diminished, it has not been eliminated.

47. Boundary Discussion:

(updated August 2018)

The eligible boundary of the General Sullivan Bridge includes the footprint of the bridge itself up to its abutments. Since the last DOE was finalized in January 2006, the north approach and north abutment have been rebuilt, and the south approach removed. Therefore, the north approach from Dover Point Road and the south approach from Shattuck Way have been excluded from the boundary of the eligible property in the current evaluation. As the north abutment is integral to the structure, its exclusion from the eligible boundary is not practicable; however, the north abutment is considered non-contributing.

The balance of the previous boundary, as established in a January 2006 addendum to the DOV0158 inventory form and confirmed in a DOE dating from the same month, remains the same.

48. Bibliography and/or References:

Casella, Richard M., for Preservation Company and NHDOT, "National Historic Context and Significance of the General Sullivan Bridge," October 2005.

Illinois Department of Transportation, http://www.quincymemorialbridge.com/, accessed July 2018.

Jergensen, Kurt, MA Department of Transportation, pers. comm. with N. Benjamin-Ma, VHB, July 5, 2018.

Roper, Stephen J. and MassDOT, "John Greenleaf Whittier Bridge," Massachusetts Historic Bridge Inventory Form (AME.927/NWB.930), revised 1990.

Vanasse Hangen Brustlin, Inc. (VHB) and HDR Engineering, Inc., for NHDOT, "Type, Size and Location Study for the General Sullivan Bridge – Dover 200/023 over the Little Bay: Newington-Dover, 11238S." March 15, 2017.

Surveyor's Evaluation:

NR listed:	individual	____	NR eligible:		NR Criteria:	A	x
	within district	____	individual	x		B	____
			within district	____		C	x
Integrity:	yes	x	not eligible	____		D	____
	no	____	more info needed	____		E	____

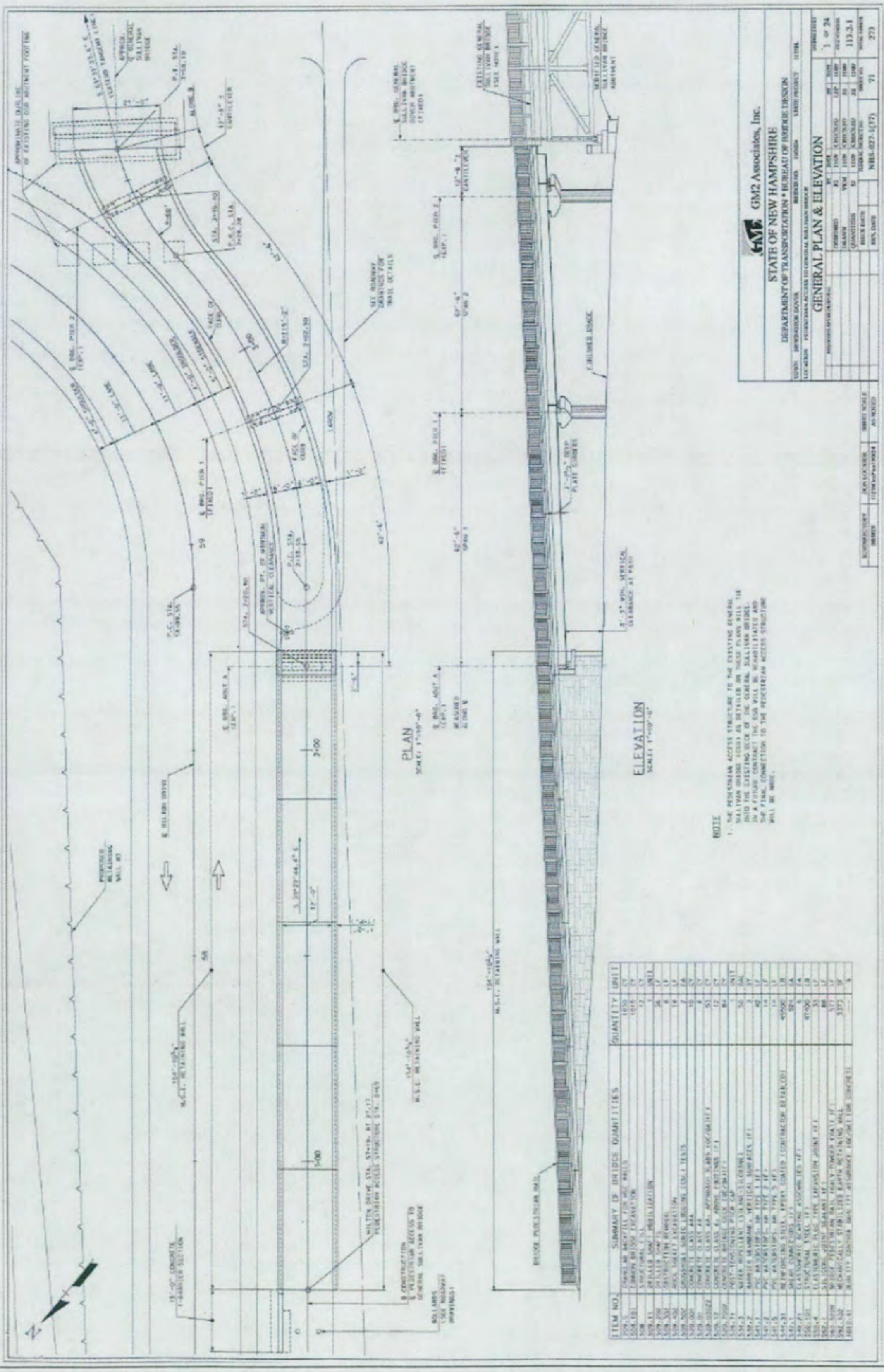


Figure 1. 2009 plans for the new north bridge approach and abutment modification, General Plan and Elevation.

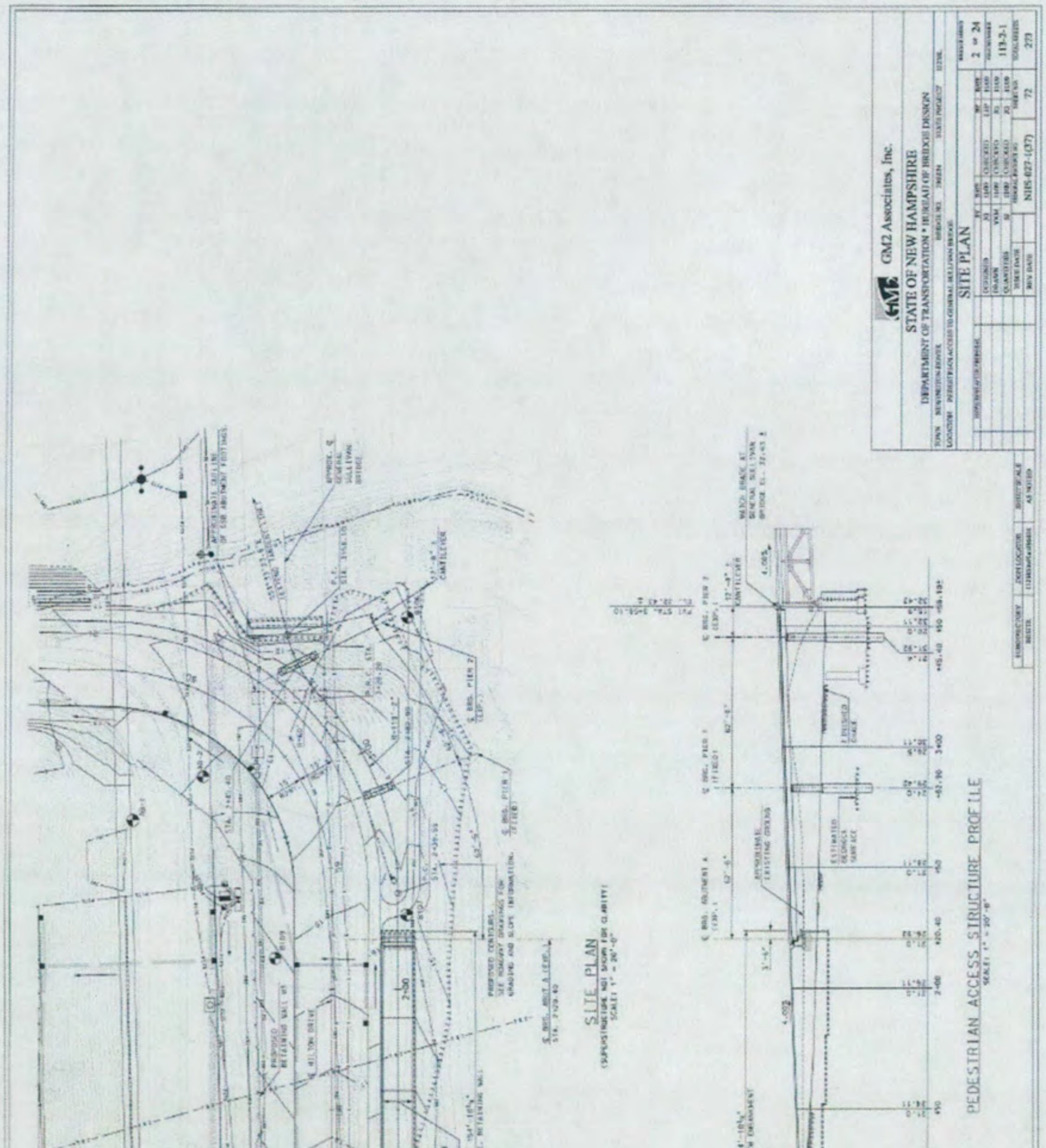


Figure 2. 2009 plans for the new north bridge approach and abutment modification, Site Plan.

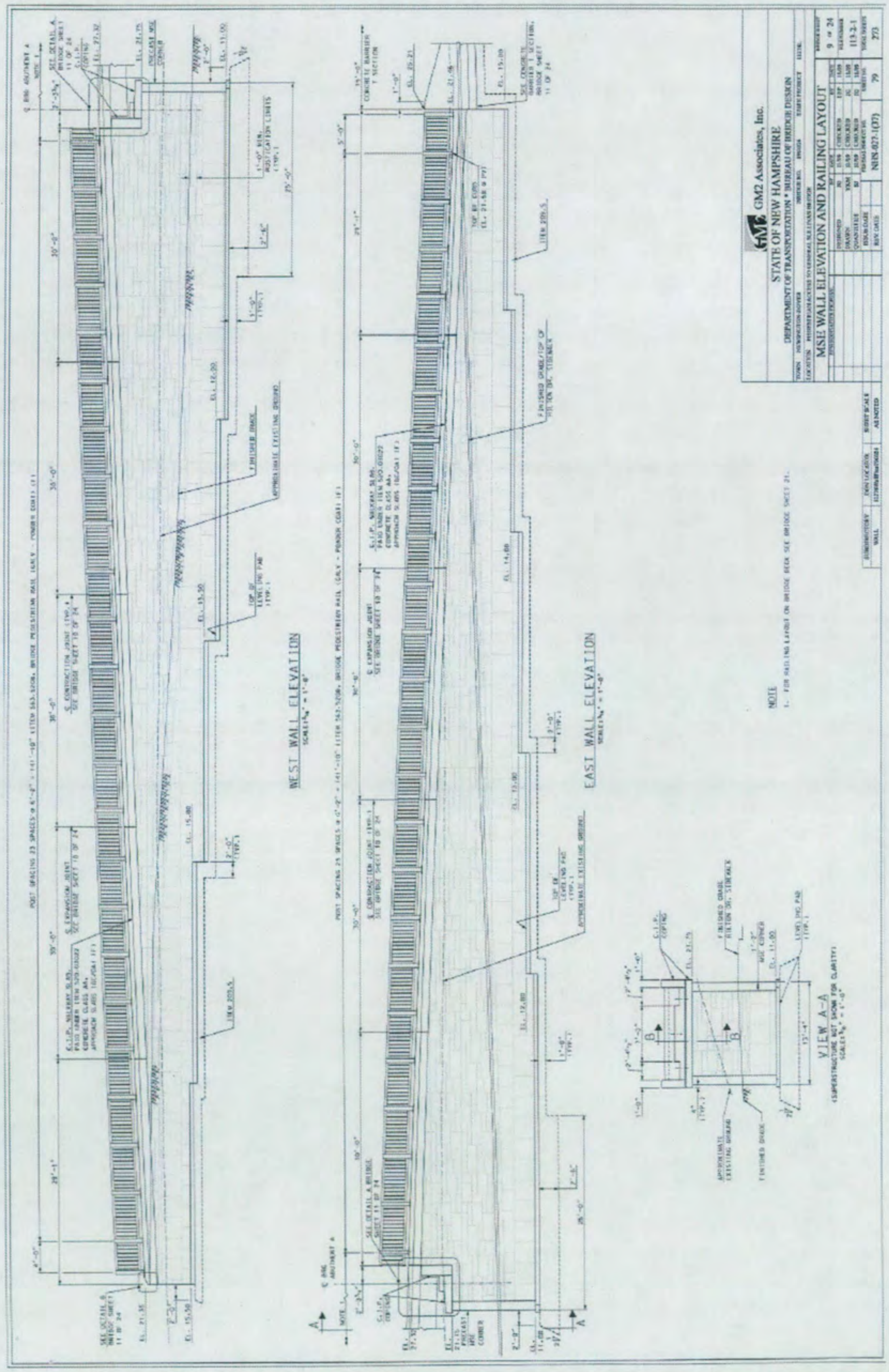


Figure 3. 2009 plans for the new north bridge approach and abutment modification, MSE Wall Elevation and Railing Layout.

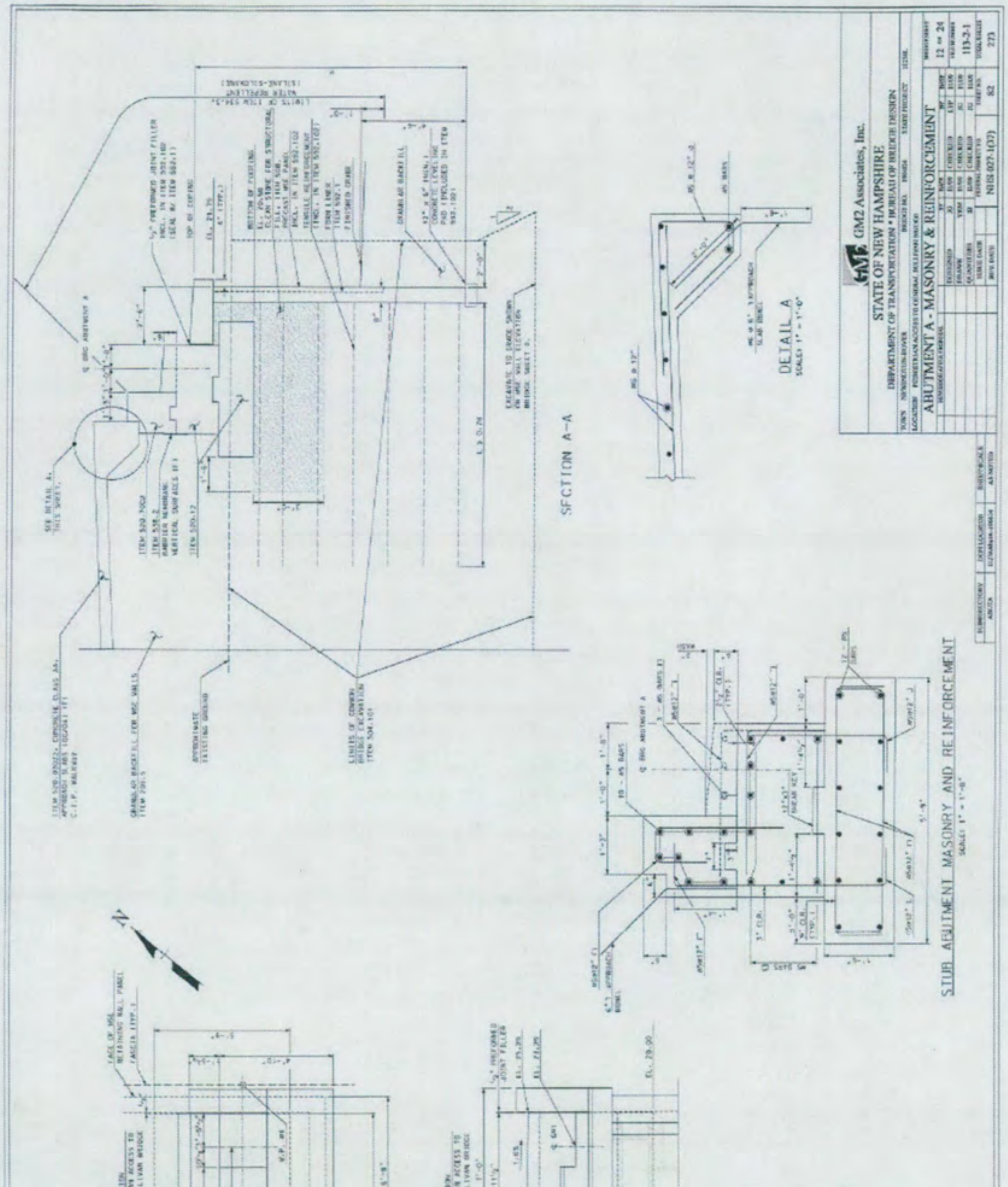


Figure 4. 2009 plans for the new north bridge approach and abutment modification, Abutment A – Masonry & Reinforcement.

Photograph Index

Photo #1	DOV0158_1	Overview of GSB, west side, from Hilton Park	Photographer facing SE	July 2018
Photo #2	DOV0158_2	Overview of GSB north approach, replaced 2011	Photographer facing SE	July 2018
Photo #3	DOV0158_3	GSB north approach, elevated ramp on right, I-girder section in center	Photographer facing SE	July 2018
Photo #4	DOV0158_4	GSB north approach, I-girder section as seen from Hilton Drive	Photographer facing W	July 2018
Photo #5	DOV0158_5	GSB north approach, abutment, and deck truss spans	Photographer facing SE	July 2018
Photo #6	DOV0158_6	Back (land side) of north abutment	Photographer facing SE	July 2018
Photo #7	DOV0158_7	Detail of connection between 2011 pedestrian approach and GSB span, north abutment (water side) in center	Photographer facing N	July 2018
Photo #8	DOV0158_8	GSB piers (right) and LBB piers (left)	Photographer facing SE	July 2018
Photo #9	DOV0158_9	Overview of GSB from Hilton Park	Photographer facing SE	July 2018
Photo #10	DOV0158_10	Center arch truss span	Photographer facing SE	July 2018
Photo #11	DOV0158_11	Entrance to north approach, constructed 2011	Photographer facing SE	July 2018
Photo #12	DOV0158_12	Overview of GSB at paved path level, showing safety fencing	Photographer facing SE	July 2018
Photo #13	DOV0158_13	Center arch truss from paved path level	Photographer facing SE	July 2018
Photo #14	DOV0158_14	Closeup of center arch truss from roadway level	Photographer facing SE	July 2018
Photo #15	DOV0158_15	View of Little Bay from GSB, Fox Point in Newington in background	Photographer facing W	July 2018
Photo #16	DOV0158_16	GSB from south approach, note LBB on right	Photographer facing NW	July 2018
Photo #17	DOV0158_17	Continuation of pedestrian path toward Shattuck Way and Nimble Hill Road from south end of GSB	Photographer facing S	July 2018

Date photos taken: July 2018

Photo # 2 Description: Overview of GSB north approach, replaced 2011
Reference (file name or frame#): DOV0158_2 Direction: SE

Photo # 3 Description: GSB north approach, elevated ramp on right, I-girder section in center
Reference (file name or frame#): DOV0158_3 Direction: SE

Photo # 4 Description: GSB north approach, I-girder section as seen from Hilton Drive
Reference (file name or frame#): DOV0158_4 Direction: W

Photo # 5 Description: GSB north approach, abutment, and deck truss spans
Reference (file name or frame#): DOV0158_5 Direction: SE

Photo # 6 Description: Back (land side) of north abutment
Reference (file name or frame#): DOV0158_6 Direction: SE

Photo # 7 Description: Detail of connection between 2011 pedestrian approach and GSB span, north abutment (water side) in center
Reference (file name or frame#): DOV0158_7 Direction: N

Photo # 8 Description: GSB piers (right) and LBB piers (left)
Reference (file name or frame#): DOV0158_8 Direction: SE

Photo # 9 Description: Overview of GSB from Hilton Park
Reference (file name or frame#): DOV0158_9 Direction: SE

Photo # 10 Description: Center arch truss span
Reference (file name or frame#): DOV0158_10 Direction: SE

Photo # 11 Description: Entrance to north approach, constructed 2011
Reference (file name or frame#): DOV0158_11 Direction: SE

Photo # 12 Description: Overview of GSB at paved path level, showing safety fencing
Reference (file name or frame#): DOV0158_12 Direction: SE

Photo # 13 Description: Center arch truss from paved path level
Reference (file name or frame#): DOV0158_13 Direction: SE

Photo # 14 Description: Closeup of center arch truss from roadway level
Reference (file name or frame#): DOV0158_14 Direction: SE

Photo # 15 Description: View of Little Bay from GSB, Fox Point in Newington in background
Reference (file name or frame#): DOV0158_15 Direction: W

Photo # 16 Description: GSB from south approach, note LBB on right
Reference (file name or frame#): DOV0158_16 Direction: NW

Photo # 17 Description: Continuation of pedestrian path toward Shattuck Way and Nimble Hill Road from south end of GSB, partially on former alignment of south vehicular approach.
Reference (file name or frame#): DOV0158_17 Direction: S

PHOTO KEY IS LOCATED ON PAGE 3, #40 "Property Map"

I, the undersigned, confirm that the photos in this inventory form have not been digitally manipulated and that they conform to the standards set forth in the NHDHR Photo Policy. These photos were printed at the following commercial printer OR were printed using the following printer, ink, and paper: Canon Pixma MG7720, Canon Photo Plus Paper Glossy, and Canon CLI-271 inks. (Color photos must be professionally printed.)
The negatives or digital files are housed at/with: VHB, Watertown, MA.

SIGNED: Nicole J. Benjamin-Ma

NH Division of Historical Resources
Determination of Eligibility (DOE)

Date received:	Jan. 19, 2006	Inventory #:	DOV0158
Date of group review:	Jan. 25, 2006	Area:	Newington-Dover Project Area (ND)
DHR staff:	Beth	Town/City:	Dover
Property name:	General John Sullivan Bridge	County:	Strafford
Address:	over Little Bay, parallel to the Spaulding Turnpike		
Reviewed for:	[X]R&C [ ]PTI [ ]NR [ ]SR [ ]Survey [ ]Other NH DOT/FHWA: Newington-Dover, NHS-027-1(37), 11238		

Individual Properties

NR SR
[X] [X]Eligible
[ ] [ ]Eligible, also in district
[ ] [ ]Eligible, in district
[ ] [ ]Not eligible
[ ] [ ]More information needed
[ ] [ ]Not evaluated for individual eligibility

Districts

NR SR
[ ] [ ]Eligible
[ ] [ ]Not eligible
[ ] [ ]More information needed
[X] [X]Not evaluated @ district

Integrity: [X]Location [X]Design [X]Setting [X]Materials
[X]Workmanship [X]Feeling [X]Association

Criteria: [X]A. Event [ ]B. Person [X]C. Architecture/Engineering
[ ]D. Archaeology [ ]E. Exception

Level: [X]Local [X]State [X]National

STATEMENT OF SIGNIFICANCE:
☐ **IF THIS PROPERTY IS REVIEWED IN THE FUTURE, ADDITIONAL DOCUMENTATION WILL BE NEEDED.**

Final information has been received regarding the eligible boundary for the Sullivan Bridge, which includes the bridge itself, its abutments and approach roads. Judging from other current project information on file at the DHR, these resources are between station 615+- in Dover and station 590 in Newington.

☒ **ENTERED INTO DATABASE**

ACREAGE:	approximately 2.5 acres
PERIOD OF SIGNIFICANCE:	1934 to 1956 (NR 50-year cut-off date)
AREA OF SIGNIFICANCE:	engineering, transportation
BOUNDARY:	as noted above and on page B1.
SURVEYOR:	Preservation Company: December 1991 and November 2004
FOLLOW-UP:	Notify surveyor and agencies.

Final DOE approved by: E H Murphy

NH Division of Historical Resources
Determination of Eligibility (DOE)

Date received: January 20, 2005 | Inventory #: DOV0158

Date of group review: January 26, 2005 | Area: Newington-Dover Project Area

DHR staff: Garvin | Town/City: Newington, N. H./Dover, N. H.

Property name: General John Sullivan Bridge | County: Rockingham/Strafford

Address: N/A

Reviewed for: [ ]R&C [ ]PTI [X]NR [ ]SR [ ]Survey [ ]Other

Individual Properties

NR	SR
[X]	[X]Eligible
[ ]	[ ]Eligible, also in district
[ ]	[ ]Eligible, in district
[ ]	[ ]Not eligible
[ ]	[ ]More information needed
[ ]	[ ]Not evaluated for individual eligibility

Districts

NR	SR
[ ]	[ ]Eligible
[ ]	[ ]Not eligible
[ ]	[ ]More information needed
[ ]	[ ]Not evaluated @ district

Integrity: [X]Location [X]Design [ ]Setting [X]Materials [X]Workmanship [ ]Feeling [X]Association

Criteria: [X]A. Event [ ]B. Person [X]C. Architecture/Engineering [ ]D. Archaeology [ ]E. Exception

Level: [X]Local [X]State [X]National

STATEMENT OF SIGNIFICANCE:

☐ **IF THIS PROPERTY IS REVIEWED IN THE FUTURE, ADDITIONAL DOCUMENTATION WILL BE NEEDED.**

Built in 1934 under difficult weather and tidal conditions, the General Sullivan Bridge was the keystone of a project that was then regarded as "the most unique and outstanding along the line of bridge and highway construction that has ever been proposed in the history of the State." Design and construction of the bridge were noteworthy achievements, described in articles in engineering journals of the time. ¶The General Sullivan Bridge was the first span in New Hampshire to be designed as a continuous arched truss, without structural breaks at its supporting piers. This design employed newly developed sophistication in analyzing stresses in continuous structures. The General Sullivan Bridge was designed by Fay, Spofford and Thorndike, bridge design specialists from Boston. Founded in 1914, this partnership was one of the most prolific American bridge engineering firms of the 1920s and 1930s. Charles M. Spofford was an authority in structural analysis who had authored a textbook, *The Theory of Structures* (1911, 1915, 1928), that outlined some of the methods of analysis for statically indeterminate structures that were employed in the design of the bridge, specifically the "Method of Least Work." In 1929, Fay, Spofford and Thorndike had designed a direct prototype for the Sullivan Bridge—the Lake Champlain Bridge, between Chimney Point in Addison, Vermont, and Fort Frederick at Crown Point, New York. ¶The Sullivan Bridge restored a long-disused travel route in southern New Hampshire. Until the bridge opened, all traffic from Portsmouth to Concord traveled first to Dover, then proceeded west through Barrington on Route 9 to join the New Hampshire Turnpike Road (Route 4) in Northwood. The Sullivan Bridge and a companion structure, the Scammell Bridge, provided a new connection with the eastern end of the old turnpike at Cedar Point in Durham. Conducting traffic along the old route through Durham, Lee, and Nottingham, the bridge thus restored usefulness to the full length of the turnpike. When New Hampshire's bridges were evaluated for historical and engineering significance in 1982, the General Sullivan Bridge attained a numerical score of 28 points, one of the highest rankings achieved by any New Hampshire bridge.

☐ **ENTERED INTO DATABASE**

ACREAGE: Less than one acre

PERIOD OF SIGNIFICANCE: 1934-1955 (arbitrary 50-year cutoff date)

AREA OF SIGNIFICANCE: Engineering, transportation

BOUNDARY: The footprint of the bridge, including the abutments

SURVEYOR: Frank Griggs and Carol Hooper, the Preservation Company

FOLLOW-UP: The inventory form needs to be edited for spelling, grammar, and phraseology. The accounts of the structural analysis and construction of the bridge need proper citations. Footnotes need to be integrated, especially a series of unconnected and discontinuous notes on page 9 of 48. The abutments and causeway of the bridge, which are part of the project, need to be described. The forms needs additional information on the firm of Fay, Spofford, (continued) and Thorndike. Under the National Register Statement of Significance, discuss the importance of Fay, Spofford and Thorndike, especially Charles M. Spofford. Discuss the design of the bridge as an early example of the application of the Method of Least Work and the Method of Three Moments to the analysis of a structurally continuous truss. The form should address the construction of the bridge as a response to a challenging set of circumstances, including rapid tidal currents, extreme cold, and ice floes. In sum, the form should discuss the national level of significance of the General Sullivan Bridge as the second and more highly refined example by Fay, Spofford, and Thorndike of a statically indeterminate continuous truss. The form also needs to supply more information on fabricators Lackawanna Steel Construction Company and Crandall Engineering Company (substructure).

Final DOE approved by:

EH Muzzey (MI)

INDIVIDUAL INVENTORY FORM **NHDHR INVENTORY NUMBER: DOV0158**

Name, Location, Ownership

1. Historic name: General Sullivan Bridge
2. District or area: N/A
3. Street and number: Route 16 (Spaulding Turnpike)/Route 4 at Little Bay
4. City or town: Newington/Dover
5. County: Strafford/Rockingham
6. Current owner: State of New Hampshire; NHDOT Turnpike Bureau

Function or Use

7. Current use(s): Vacant/Not in use
8. Historic use(s): transportation, road-related

Architectural Information

9. Style: NA
10. Architect/builder: Fay, Spofford & Thorndike (Engineer)/Lackawanna Steel Construction Company (Contractor for Superstructure)/ Crandall Engineering (Substructure)
11. Source: Various
12. Construction date: 1934
13. Source: Various; See below
14. Alterations, with dates: Minor repairs to roadway surface, sidewalk, piers, etc.(see alterations section)
15. Moved? no ☒ yes ☐ date: N/A

Exterior Features

16. Foundation: concrete
17. Cladding: N/A
18. Roof material: N/A
19. Chimney material: N/A
20. Type of roof: N/A
21. Chimney location: N/A
22. Number of stories: N/A
23. Entry location: N/A
24. Windows: N/A
    Replacement? no ☐ yes ☐ date: N/A

Site Features

25. Setting: Rural; Parallel to Four-lane Highway

35. Photo 1 36. Date: December 2004
37. Roll: 2004-21 Frame: 21 Direction: E
38. Negative stored at: NHDHR

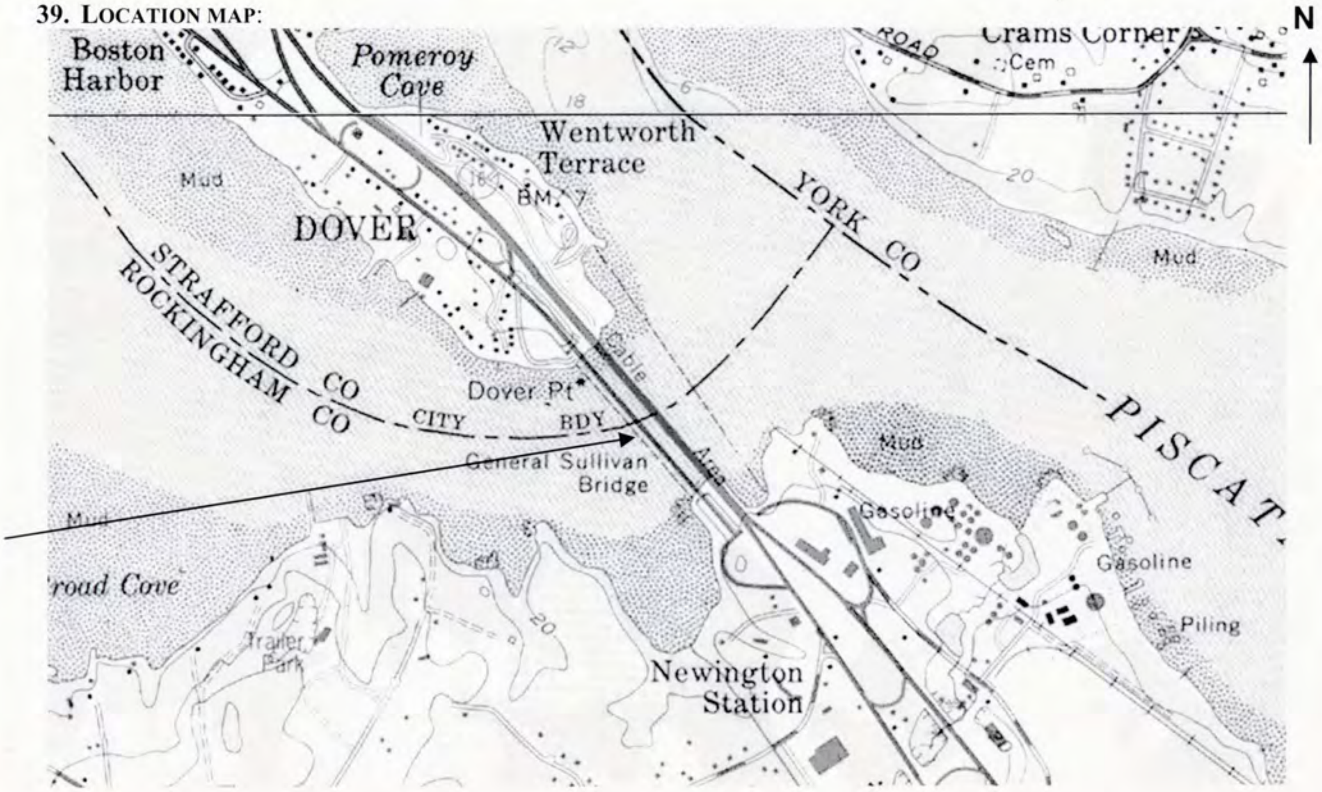
26. Outbuildings: N/A
27. Landscape features: Little Bay
28. Acreage: less than 1 acre
29. Tax map/parcel: N/A
30. UTM reference: 19.351415.4775280
31. USGS quadrangle and scale: Portsmouth, 1:24000

Form prepared by

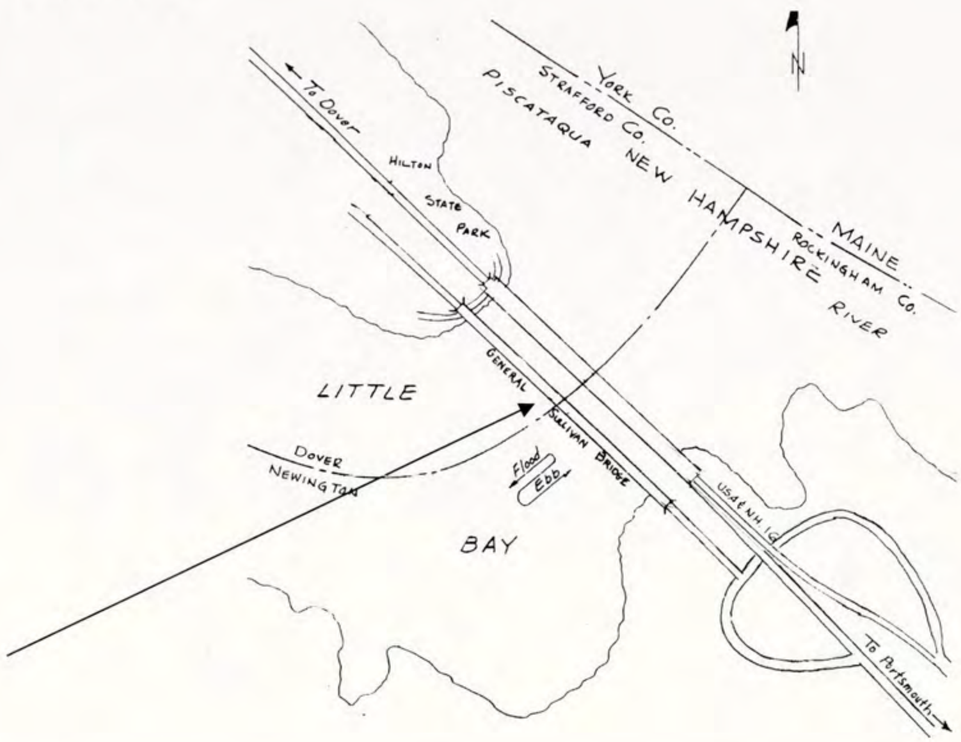
32. Name: Richard Casella, Frank Griggs, Carol Hooper
33. Organization: Preservation Company
34. Date of survey: November, 2004

NH STATE PLANE NAD 83 (FT)
X = 1208819 Y = 226438

39. LOCATION MAP:



40. PROPERTY MAP:



41. Historical Background and Role in the Town or City's Development:

Located between the towns of Newington and Dover, New Hampshire, the General Sullivan Bridge[1] is poised on the eastern boundary of New Hampshire between points of land at the confluence of Little Bay (to the west) and the Piscataqua River (to the east). The bridge's location allows traffic traveling between Portsmouth (and points north) and areas of New Hampshire to the north and west (such as the Lakes region) to avoid the long 11-mile detour around Little and Great Bays. Little Bay is the narrower, eastern and northern part of the Great Bay Estuary system that dominates this area. The location of the General Sullivan Bridge has particularly strong tidal currents. Great and Little Bays act as a reservoir that is filled and emptied with the change in tide; because the opening at the location of the bridge is relatively narrow, currents of up to 8 miles per hours are created.

The General Sullivan Bridge unites the towns of Newington and Dover; running between Dover Point (to the north) and an area in Newington near Bloody Point (to the south). The water is the also the dividing line between Rockingham and Strafford Counties and immediately to the east of the bridge (in the Piscataqua River) is the boundary between Maine and New Hampshire.

Although now bypassed, the General Sullivan Bridge was part of both the Spaulding Turnpike (Rt. 16) and Route 4. The former is the primary route north from the seacoast area of New Hampshire to the White Mountains and Lakes Region. Constructed beginning in 1953, the 11.2-mile long turnpike runs southeast to northwest, from Portsmouth to Milton, north of Rochester. The Bridge also was part of Route 4 and connected the western side of the state, Concord and Durham, to Portsmouth and the eastern seaboard.

The General Sullivan Bridge is an 8-span steel deck and thru truss bridge designed by the firm of Fay, Spofford & Thorndike and completed in 1934. The bridge is eligible for the National Register of Historic Places, at a national level of significance, in the area of engineering. It is an important early example of a continuous truss highway bridge and its design and construction made a significant contribution to the advancement of twentieth century American bridge technology. The bridge is one of four major bridges of the same type, style and time period designed by the firm of Fay, Spofford and Thorndike, that as a group significantly influenced future continuous truss highway bridge design in the areas of technology, aesthetics and construction methods. Because of its primary importance to the bridge's significance, a discussion of the engineering background and significance of the bridge will precede the discussion of the bridge's background and more general historical significance.

<u>Engineering Significance of the Sullivan Bridge and Evolution of Continuous Truss Railroad and Highway Bridges in the U.S.</u>

Up to the mid-twentieth century, most bridges were simply supported, meaning that the girders that supported the deck ended at each pier or support. Continuous girders, that is, girders that spanned intermediate piers, on the other hand, were first used experimentally beginning in the mid-nineteenth century. The long term switch to continuous design for certain types of bridges offered a number of advantages to designers, including a reduction in the amount of materials, a more streamlined appearance, and reduced deflection and vibration. Disadvantages included a more complicated design process (in specific, the fact that the various stresses could not be exactly calculated thus were "indeterminate") and greater sensitivity to the effects of unequal settlement of the substructure.

[1] The official title of the General Sullivan Bridge is "The General John Sullivan Memorial Bridge," however it has always been generally referred to simply as the General Sullivan Bridge.

The first use of continuous trusses in the U.S. was for railway bridges. Prior to the mid-1920s, only a few large continuous truss bridges had been constructed to carry railroads over large rivers and with one exception, all dated from 1917 or later. For obvious reasons the great advances in American bridge technology during the late nineteenth and early twentieth centuries were primarily the work of the railroads.

Most historical engineering texts and papers credit the introduction of the continuous truss bridge to America to nineteenth century railway bridge engineer, Charles Shaler Smith. The Lachine Bridge, designed by Smith and built 1887-1888 to carry the Canadian Pacific Railway over the St. Lawrence River near Montreal, was a monumental structure with two central thru-spans of 408' each and two side spans of 269' each (Merriman and Jacoby 1912:32).[2] The Lachine Bridge was considered to be the only continuous truss of "any importance" built in America until 1915.

That year marked the beginning of construction of another continuous truss railway bridge, the Sciotoville Bridge, which carried the Chesapeake and Ohio Northern Railroad over Ohio River (Waddell 1916: 25). The Sciotoville Bridge was designed by Gustav Lindenthal, a brilliant Austrian-born engineer who came to America in 1874, built several of the country's greatest bridges including the highly acclaimed Hell Gate Arch Bridge, and ultimately became known as the "Dean of American Bridge Engineers" (American Society of Civil Engineers 1972: 81). When completed in 1917, the Sciotoville Bridge – with two continuous spans of 775' each – was the longest and heaviest fully riveted truss in the world, a title it retained until the building of the 839' Duisberg Bridge in Germany in 1935 (*Encyclopedia Britannica* 1954:126). Through his works and his writings, Lindenthal became a leading authority and proponent of the continuous truss bridge right up to his death in 1935.

Articles on the Sciotoville Bridge in engineering journals generated further interest in the continuous truss type (*Engineering News* 1915: 64-66; *Engineering News* 1917: 343-344; Lindenthal 1922: 910-975). A detailed series of articles on the building of the bridge by C. B. Pyle, field engineer for McClintic-Marshall Company, the fabricator and erector of the bridge, furthered the understanding of the practical technicalities involved in their construction (Pyle 1918B:62-68; Pyle 191C: 219-227; Pyle191A:1182-1186). The American Bridge Company, McClintic-Marshall's larger competitor, embarked on their own continuous-truss research and development project, and in 1918 designed and completed the second major bridge of the type in the U.S. to carry the Bessemer & Lake Erie Railroad over Allegheny River at Pittsburgh (*Engineering News*-Record 1918A: 848-856). The Bessemer and Lake Erie Bridge consisted of two 3-span continuous units, the longest span being 520'. Also in 1918, Canadian engineers completed the Hudson Bay Railway Bridge over the Nelson River in Manitoba with a 400' center span and two 300' side spans (*Engineering News-Record* 1918B:388-393).

Discussion of the economical applications of continuous bridges and the analysis of indeterminate structures and secondary stresses followed these pioneering structures and continued through the 1920s and into the 1930s. Papers and textbooks on the subject were published by many of the leading engineering professors and practitioners.[3]

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[2] For a detailed description of the Lachine Bridge see *Engineering News*, October 1, 8, 15, 1887.

[3] In 1919 British engineer Ewart C. Andrews published the complete English translation of Castigliano's 1879 "Theorie de l'equilibre des systemes elastiques et ses applications" under the title *Stresses in Elastic Structures*. See also Westergaard 1922: 576; Ammann 1924: 666-668; von Abo 1926:1-193; Parcel and Maney 1926; Nishkian and Steinman 1927:1-143; Cross 1927:610-626. Two textbooks that entered the structural analysis field in the mid-1930's should be noted: The *Analysis of Engineering Structures* by A.J.S. Pippard and J.F. Baker in 1936, and *The Theory of Continuous Structures and Arches* by Charles M. Spofford in 1937.

Lindenthal's detailed account of the design of the Sciotoville Bridge in the *Transactions of the American Society of Civil Engineers* garnered comments from such learned engineers of the day as C.A.P. Turner, J.E. Greiner and D.B. Steinman (Lindenthal 1922:910-975). Most debate hinged on the economy of continuous versus simple span truss designs because Lindenthal had not only advocated the continuous span in place of the long-span cantilever, but also as an economic alternative to simple truss spans in many lesser-span situations. After a lengthy and detailed argument, Professor Turner found that while Lindenthal "discloses meritorious details in advance of current practice," his conclusion on the economical virtues of the continuous truss for moderate spans "differs from the majority opinion of American bridge engineers because of lack of demonstrated economy on a scientific mathematical or design basis" (Turner 1922: 954, 961).

Lindenthal effectively rebutted Turner's economic argument by explaining that the added stiffness and greater resistance to impact and wind loads afforded not only by the continuous girders, but by the continuous lateral bracing, produced a better bridge better suited for high levels, high wind areas and high speed traffic, and would prove economical in that respect not only for moderate but shorter spans as well (Lindenthal 1922: 971-975).

Steinman was squarely in Lindenthal's camp, calling the continuous truss:

> an excellent bridge type, offering decided advantages (under suitable conditions) over practically all other forms of construction...its general adoption for fixed spans has long been retarded by prejudices based on erroneous notions...a proper comparison with corresponding simple spans will generally show a substantial saving of material in favor of the continuous structure. (Steinman 1922: 964).

Another landmark paper which provoked extensive discussion and much acclaim was entitled "Secondary Stresses in Bridges" by Cecil von Abo published in 1926 (von Abo 1926:1-193). Abo compared the various methods pertaining to secondary stresses, applying each to a 150' Warren truss railroad bridge. The ensuing discussion again showed fundamental and complex disagreement among engineers as to the preferred method of solving for secondary stresses and even the importance of doing so.

The history of the use of continuous trusses for highway, rather than railroad, bridges begins in 1927. Lindenthal again led the way with what is apparently the first modern continuous truss highway bridge of indeterminate design in the U.S. of significance, the Ross Island Bridge over the Willamette River in Portland, Oregon, completed in 1927 (Figure 1). The Ross Island Bridge incorporated an arched center span of 535' and half-arched side spans of 321' with a concrete slab roadway carried above (Lindenthal 1932:424). Lindenthal completed another continuous truss highway bridge over the Willamette in Portland in 1927 as part of the same commission, the Sellwood Bridge. It was also a deck bridge but with parallel-chord trusses and a maximum span of 300'. Lindenthal built two continuous truss highway bridges of determinate design in 1880 and 1890 based on the counterweighted funicular principal (Lindenthal 1932:423).[4]

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[4] It could not be conclusively determined from a review of the literature who built the first continuous truss highway bridge in the U.S., but it appears to have been Lindenthal. In 1932 Lindenthal wrote an article entitled "Bridges with Continuous Girders" in which he reviewed the American practice over the previous fifty years. Lindenthal studied various designs for continuous truss bridges in 1883 and in that year built a variation of the type using the "funicular principle" with counterweights at the piers to balance the stresses in the trusses. The Herr's Island Bridge carried a highway over the Allegheny River near Pittsburgh with three thru-spans of 200'-300'-200'. In 1890 he built another bridge on the same

The Ross Island and Sellwood bridges did not receive major coverage in the engineering literature at the time of their completion. One small article discussed the unique method of closing the arch of the Ross Island Bridge without jacking that instead utilized the careful calculation of the expansion of the steel truss due to the daily temperature change (*Engineering News*-Record 1926: 796-797).

Lake Champlain Bridge

Following right on the heels of Lindenthal was the engineering firm of Fay, Spofford & Thorndike (FS&T) who in 1927 began the design of a long-span continuous arched truss bridge to span Lake Champlain. The bridge was an innovative and highly aesthetic design with the roadway deck carried above the side trusses and through the arched center truss (Figure 2). The bridge was called "ingenious" for its deck layout that "provided the necessary clearance at mid-span with such economy in the approaches" (Abbett 1933: 654). Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike were all highly accomplished bridge engineers and their firm's bold design must have been partly driven by a desire to establish prominence in the rapidly expanding field of long-span highway bridge design[5].

It was agreed at the outset by both the engineers and the owner (Joint [Bridge] Commission of New York & Vermont) that the bridge "should have as pleasing an appearance as possible" due to its conspicuous height and the historic importance of the site (Spofford 1933: 632). In designing the Lake Champlain Bridge, Spofford stated that he "found it impossible to sketch any simple span design that was at all satisfactory in appearance" (Spofford 1933: 633). He also considered cantilevered and suspension bridges, but discounted each for various reasons, settling finally on the continuous type, which he decided "can be given a more pleasing appearance, consistent with economy, than any of the other types of truss bridges" (Spofford 1933: 633). Design of the Lake Champlain Bridge was begun August 2, 1927, and the final plans accepted November 15, 1927 (Spofford 1933:624). This places the FS&T design at the very forefront of continuous truss highway bridge construction in the U.S.

The innovative and highly successful integration of aesthetics into long-span truss design by Fay, Spofford & Thorndike was a significant development. American bridge engineering treatises have included extensive sections on the aesthetic design of bridges since the late nineteenth century. Bridge designers were instructed to consider the fundamental principles of artistic design in the order of their importance: symmetry, style, form, dimensions, and ornamentation. Occasional commentaries on the elements of good aesthetic design and beauty as it pertained to bridges appeared in the engineering press in the early twentieth century, but it was during the 1920s that the movement picked up considerable speed, coinciding with the larger societal movements toward aesthetically designed public spaces like the City Beautiful movement. Partially in answer to advancements in the aesthetic designs of concrete bridges, beginning in 1929 the American Institute of Steel Construction (AISC) established an award to be given annually to the "most esthetic solution to a problem in steel construction." The first award was given retroactively to the 6th Street Suspension Bridge in Pittsburgh completed in 1928. For 1929 it was decided to give three awards, one for long span bridges, one short span and one honorable mention, the latter given to the Lake Champlain Bridge (*Engineering News-Record* 1930:225).

principle to carry highway and streetcar traffic over the Monongahela River at McKeesport. Lindenthal abandoned the funicular principle and it was not until the late 1930s that the principle was incorporated into the patented Wichert Truss system to combine the advantages of continuity with a statically determinate design.

[5] See later section of this form for biographical information.

The AISC's director of engineering services, F.H. Frankland, presented a paper to the Canadian Good Roads Association in 1929 in which he noted that the possibilities for continuous bridge design was now recognized by engineers and continued to gain their favor. The bridge type had "generally come to be accepted as the full equivalent of other types where field erection conditions and economy in material permit" (Frankland 1929:170). Continuous trusses were increasingly being found more economical than cantilevers for long span highway bridges. The first continuous-truss highway bridge over the Missouri River was designed by the firm Sverdrup and Parcel and completed in 1929 at St. Joseph, Missouri (*Engineering News-Record* 1929A: 100-102). The bridge had two 450' thru-spans and resembled a cantilever design with panels of varying depth increasing to a maximum over the center pier. The next year the Strauss Engineering Company of Chicago spanned the Mississippi at Quincy, Illinois with a parallel chord truss design that incorporated two-spans of 627' each and established a new record for continuous truss highway bridges (Pesses 1930: 572-575). The design of these two bridges demonstrated the potential economy afforded by the type when aesthetic considerations are removed from the equation[6].

Little Bay/General Sullivan Bridge

Following on the success of the Lake Champlain Bridge, FS&T was contracted for design and construction supervision of the Little Bay Bridge by the New Hampshire Toll Bridge Commission on April 11, 1933[7]. Upon the bridge's completion in 1934, it was well received by both the lay public and the engineering community. *Engineering News-Record* called the General Sullivan Bridge and the companion Ballamy River trestle bridge "exceptional structures, which are notable in design and particularly for the construction methods employed"(*Engineering News-Record* 1934B: 387).

The design followed the acclaimed Lake Champlain Bridge with the same innovative arrangement of deck side trusses and arched center thru truss that reduced the height and cost of the approach grades while achieving the necessary high-level channel clearance. The Little Bay Bridge represented an important step in the evolution of the continuous truss highway bridge for three reasons: it incorporated **special features** of the FS&T prototype that were proved economically sound; its construction demonstrated the practical application of a **new technology** for weighing bridge reactions; and it established, or helped establish, a markedly **reduced economical span length** for the continuous truss.

On the first of these, the special features of the bridge included the innovative deck layout previously discussed, and the use of a state-of-the-art concrete deck design. The slab was reinforced with "welded bar trusses spaced 6 inches between centers and welded into mats by adding spacer bars across the trusses" (Spofford 1935:6). This is an early use of so-called "unit trusses" for reinforcement, but exactly how early was not determined. Another deck feature was the two-layer construction with the top wearing surface separated from the structural slab by a burlap "cleavage fabric to permit the top layer to be removed if it wears out without disturbing the floor-slab" (Spofford 1933:647). The design of the dove-tailed sliding-plate deck expansion joints and the

[6] With all this attention and awards being heaped on continuous trusses, Lindenthal came forward to set the historical record straight on his priority and preeminence in the business with an article in Civil Engineering (1932) entitled "Bridges With Continuous Girders; Reviewing Half A Century of Experience in American Practice" (Lindenthal 1932:421-424). Lindenthal described his experiments with funicular bearing bridges in the nineteenth century, but made a special point of mentioning Spofford's 1931 article on the Lake Champlain Bridge, noting, "A similar structure, the Ross Island Bridge, having arched continuous girders, was built under my supervision in 1925-1927" (Lindenthal 1932:423).

[7] Information about the

double-stepped curbing were also mentioned in the articles on the bridge as being of note (Spofford 1935:6-7; *Engineering News-Record* 1934B: 387).

A second important innovation of the Little Bay/General Sullivan Bridge was Spofford's method of weighing bridge reactions in the field by using newly developed proving rings of unprecedented accuracy to adjust the end reactions on the bridge (Spofford 1935: 12, 14). This was the first time the method had been used on a large continuous bridge. Spofford went on to use the rings on the later Bourne and Sagamore bridges and published the results of his findings in a 1935 article (Spofford and Gibbons 1935: 446-449).

The determination through field measurement of the actual exact weight that a continuous bridge bears down upon each of its supporting bearings is necessary to confirm that the erected structure conforms with its mathematical design. Spofford states "the assumed reactions at the piers are seldom if ever attained because of such things as changes in the relative elevation of the piers, variations in the modulus of elasticity of built-up steel members, and differences in length of the various truss members as they come from the fabricating shop" (Spofford and Gibbons 1935: 446).

Weighing and adjusting the reactions of continuous bridges was done by Lindenthal and others with hydraulic jacks coupled to pressure gages and with strain gages. Spofford used hydraulic jacks with gages on the Lake Champlain Bridge but found the method to be unsatisfactory due to the inability to measure the friction in the jacks and to maintain the gages in calibration in the field (Spofford and Gibbons 1935: 446).

The proving rings used by Spofford were patented in the mid-1920s and consisted of round steel "donuts" with sensitive measuring instrumentation inserted within the ring. When a load was placed on the rings its deformation could be measured with extreme accuracy. The proving rings used to measure and adjust the General Sullivan Bridge were manufactured by Morehouse Machine Company of York Pa., and were of 200,000-pound capacity with an accuracy guaranteed to one-tenth of one percent. The rings were actually sensitive enough to detect differences as small as two pounds and the operator found he could detect disturbances due to a man standing on the bridge (Spofford 1935:14). The first use of proving rings in bridge construction was in 1933 when David S. Fine, an erecting engineer with the American Bridge Company, used the devices to measure the reactions of a bascule bridge the company built in New Jersey. Spofford was the second to use the rings, and the first to utilize the method for continuous truss construction (Spofford and Gibbons 1935:447).

The third and final important feature of the Little Bay/General Sullivan Bridge, although overlooked in the engineering literature at the time, was its main span length of 275' and continuous unit length of 675'. These lengths approached nearly half the length of the Lake Champlain and French King bridges and may have constituted the shortest continuous arched truss built to date. This is significant because in the case of the continuous truss, the trick was to demonstrate that the type could be economically suited for shorter spans, not longer spans. Each type of bridge has a range of span length for which it can be used to advantage over other types, adjusted for variables such as site conditions and loading. In the overall development of highway bridges during the expansion of the nation's highway systems, improving the economy and aesthetics of short-to-moderate spans was far more important than the few record setting long-span bridges that garnered the greatest attention. The addition of a very aesthetically appealing truss design that could be built with the cantilever construction method and prove economical for medium span lengths was an important advancement.

Bourne and Sagamore Bridges

The Bourne and Sagamore Bridges were designed by FS&T for the Army Corps of Engineers to span the newly enlarged Cape Cod Canal, these bridges completed FS&T's quartet of early continuous truss bridges (Figure 4) (*Engineering News-Record* 1934A: 107-109; *Engineering News-Record* 1934C: 607; *New York Times* 1935:11). The Bourne Bridge opened first in 1934 and received the AISC "Class A" award for most beautiful steel bridge of that year; the Sagamore Bridge opened in 1935 and received honorable mention in the Class A category(*Engineering News-Record* 1935B: 857; *Engineering News-Record* 1936: 28). The three-span continuous arch unit is identical on the two bridges, with the Bourne Bridge additionally equipped with two simple deck-truss approach spans at each end.

With the economical short-span length established for their trademark continuous truss design by the General Sullivan Bridge, the Cape Cod Canal project now presented FS&T the opportunity to establish a new long-span length for their design. At 616', the Bourne and Sagamore spans exceeded the Ross Island Bridge by 81' and were just 11' shy of the record span length for a continuous-truss highway bridge apparently set in 1930 by the Quincy Memorial Bridge over the Mississippi River at Quincy, Illinois (Pesses 1930: 572-575). These two long bridges however, were still roughly 150' shy of Lindenthal's 1917 Sciotoville railroad bridge.

In addition to the 40 percent increase in span length that the Bourne and Sagamore bridges represented over the Lake Champlain Bridge, they were designed to use high-strength silicon steel. Although the steel cost was 12.8 percent more than ordinary carbon steel, the stronger steel allowed a reduction in the size and cost of the individual members and resulted in a savings of approximately $50,000 for the two bridges (Spofford 1936: 168). This was not the first use of silicon steel in continuous truss highway bridge construction, at least two other bridges, the 1929 Missouri River Bridge at St. Joseph and the 1930 Quincy Memorial Bridge over the Mississippi made extensive use of it (Sverdrup 1929: 100-102; Pesses 1930:572-575).

The Cape Cod Canal bridges also differ significantly from the Lake Champlain and General Sullivan Bridges in the profile of the arch and the roadway locations, as shown in Figures 2, 3, and 4. The longer span required a deeper truss and taller arch. In order to keep the roadway grades within prescribed limits, the deck was suspended from the arched truss rather than carried at the level of the lower chord members. This arrangement was dictated primarily by site conditions, specifically the required channel clearance opening of 135' high by 500' wide, and the limitations of the possible approach configurations.

The Influence of the FS&T Continuous Truss Design on Later Bridges and the End of the Development Period

The mid-1930s appear to mark the end of what can be considered the development period of the continuous truss bridge in the U.S. The type began to see broad use in a wide range of spans and the AISC continued to give the type awards nearly every year. Referring to bridge developments in 1937, A.L. Gemeny, senior structural engineer for the U.S. Bureau of Public Roads said "in the field of steel bridges multiple simple spans have almost gone into discard...continuous beam and girder spans are being generally adopted for intermediate lengths ...for long spans continuous trusses and cantilevers are used" (Gemeny 1938: 233-234).

In 1935 two major bridges designed by the firm of Waddell and Hardesty were completed over the north and south branches of the Niagara River to Grand Island (Figure 5). The south bridge was a near copy of the Cape Cod design with a center thru-span and a suspended deck, the north span was a deck bridge. Both Grand Island bridges had more deeply arched side spans than the FS&T

designs, which were essentially flat. The north bridge with the deck truss won the AISC "Class A" award for 1935, beating the Sagamore Bridge which received honorable mention (*Engineering News-Record* 1936: 28).

Non-arched two-span thru-trusses like the 1929 St. Joseph Bridge over the Missouri River and the 1930 Quincy Bridge over the Mississippi continued to be the preferred design for continuous truss bridges over the big mid-west rivers. Two examples are the mile-long Missouri River bridge at Omaha with a two-span continuous truss of 1050' overall, completed 1935 (Figure 6) and the Mississippi River bridge at Hannibal, with a two-span continuous truss 1125' long, completed in 1936 (*Engineering News-Record* 1935: 727-732; Parcel 1936: 362-364). Continuous deck trusses were also seeing more widespread use in approaches to the big river bridges, as shown by the three-span continuous-truss deck units of 222' span that were used as approach spans to the 740' suspension span of the Mississippi River Bridge at Davenport, Iowa (*Engineering News-Record* 1935C: 837-841).

State highway departments continued to gain confidence in designing continuous bridges in-house. The Kansas Highway Commission adopted continuous spans and built rolled-beam, plate-girder and continuous truss bridges with an estimated savings of 10-30 percent over simple spans (Lamb 1935: 702-706). The Montana Highway Department also "turned definitely to continuous spans" and in 1938 extended the possibilities of the short-span arched continuous truss highway bridge with a three-span deck truss (84'-168'-84') over the Middle Fork of the Flathead River at Belton Montana. The bridge was built at an amazing cost of only $74,815 and won the AISC Class C award for 1938 (Maun 1938:186; *Engineering News-Record* 1939: 39).

The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T was copied for years to come for major and minor highway bridges around the country where aesthetics and cantilever construction were necessary factors. As new bridge technologies and design concepts developed they were integrated into the design type to create hybrid forms of continuous arched truss bridges. The monumental 53-span Susquehanna River between Havre de Grace and Perryville, Maryland, designed by J.E. Greiner and completed in 1941, used two three-span units identical in appearance to the Cape Cod Canal bridges, but supported by pinned Wichert rhomboid panels over the piers to make them statically determinate structures (*Engineering News-Record* 1940:7; *Engineering News-Record* 1941:114). The 1949 Julien Dubuque Bridge over the Mississippi at Dubuque, Iowa established a new world's record for a continuous truss by using the deck structure in tension to tie the 845' main arch span. The tie allowed a 25 percent reduction in the height of the arch resulting in significant savings in material and erection costs (Bergendoff and Sorkin 1949: 1273-1305) (Figure 7).

Historical Background and Significance of the General Sullivan Bridge

<u>History of the Crossing</u>

The two points of land that the General Sullivan Bridge unites were important in the earliest history of New Hampshire settlement and were soon a vital part of the transportation network of the region. Dover Point was settled in 1623; it was the second site of European settlement in the region. Due to its pivotal location on the Piscataqua, and its wealth of natural resources including lumber and clay, Dover Point was significant throughout the region's historical development. It was a maritime transportation and shipbuilding center, the site of farming and extensive brick manufacturing, and a land and rail transportation corridor between the state's only seaport and the interior. The earliest settlement in Newington, which was originally included in Hilton's Grant (Dover), was ca. 1670 at Bloody Point.

Given its key location and early settlement, the site of the General Sullivan Bridge was, logically, one of the earliest water crossings in the state. Ferry service between Bloody Point in Newington and the southern tip of Dover Point (the Bloody Point Ferry) began as early as 1640; it served as the only early connection between Portsmouth, Dover and the up-country settlements. The first ferry was operated by the Trickey family from 1640 to 1705. Thereafter, the ferry was owned by John Knight who operated Knight's Ferry until 1725. Later, the ferry was based on the north side of the crossing, and was run by the Henderson family (Chesley 1984:23).

Transportation routes in the area changed in 1794 when a group of private investors funded the construction of the Piscataqua Bridge as an alternate route across Little Bay. This famous early bridge was located between Fox Point in Newington and Cedar Point in Durham a few miles to the west of where the General Sullivan would later be built. The location was selected because it was an easier site to erect a bridge; it had the advantages of having two islands (Goat Island and Rock Island) in the middle of the channel and of having weaker tidal currents. The bridge was integral to the construction, around 1800, of the First New Hampshire Turnpike that connected Portsmouth and Concord.

The Piscataqua Bridge consisted of a trestle structure over the shallow portions of the river on each end, and a soaring timber arch over the deeper channel. Timothy Palmer designed and built the 244' long main arch and Major Zenas Whiting of Norwich, Connecticut, built the trestle approach structures on either side as well as a small draw span for high masted boats on the Durham side. Due to its length and aesthetic design, the bridge achieved some national notoriety. The Bridge's span of 244' remained the longest simple span in the United States until 1812

With the new bridge in operation, the ferry from Dover Point continued on a reduced scale. The bridge's construction, however, meant that the center of activity shifted westward toward Durham for a period of sixty years. The bridge site was difficult however, and was subject to currents and ice jams. Although the Piscataqua Bridge had major repairs in 1803 and was largely rebuilt in 1830, it gave way in 1854 and was not repaired. An ice jam on February 18, 1855 took 800' of the trestle work on the Newington end of the bridge and the bridge was taken down. For nearly twenty years, there was no bridge across Little Bay. Commerce was again dependent on ferry and gundalow traffic in the region.

This changed in 1873 with the construction of the Portsmouth-Dover Railroad Bridge over Little Bay, which was located a few hundred yards downstream of where the General Sullivan Bridge was built sixty years later. The bridge's location was to affect the pattern of traffic in the region up to the present. The Portsmouth and Dover Railroad was financed largely by wealthy local brewer Frank Jones, who needed a way to get grain to his Portsmouth breweries. The railroad ran northwest out of Portsmouth along the shore of the Piscataqua in Newington and crossed the water between Bloody and Dover Points, continuing north up Dover Point. This new bridge carried both the railroad and a roadway. Overall it was of traditional pile and trestle construction (Chesley 1984). A 193'-long section was a Howe truss covered bridge with timber and iron tension rod between each panel. The swing span was 143' long leaving openings on both sides of approximately 50'. The wooden pile-supported trestle was 1,294' long in total, with a 192' through wooden truss resting on masonry piers. The total length of the bridge was 1,635'. The width of roadway was 14' on the truss and swing span and 17' to 18' on the trestle sections. The truss span replaced a portion of trestle spans around 1885 (Fay, Spofford & Thorndike and Henderson 1936:9). The road was formally opened to public travel February 9, 1874.

After 1900, the Portsmouth and Dover was operated as part of the Boston and Maine network. Like it predecessor to the west, the bridge between Newington and Dover Point was often damaged by currents and ice jams, including a serious failure during World War I. At the same time, automobile traffic over the bridge increased. Woodbury Avenue, River Road and Dover Point Road, all feeder roads to the bridge, became part of the first set of State highways, the East Side State Road, after the Trunk Line system was established in 1905. This later became NH Route 16. It was also the beginning of U.S. Route 4, which followed Dover Point Road into Dover and went west through Barrington toward Concord on what is now Route 9 (U.S.G.S. 1918, 1941).[8] In April 1933, the State of New Hampshire purchased the old bridge. Soon thereafter, by the time work had begun on the new General Sullivan Bridge, the railroad had abandoned the railroad line going north, and was no longer using the tracks on the bridge. The bridge was removed in the spring of 1935 with the opening of the General Sullivan Bridge.

The Legislative Effort to Build a Bridge Crossing Little Bay

The eight-year effort to construct a new bridge across Little Bay, which culminated in the construction of the General Sullivan Bridge, had a long, contentious and quite complicated political and legislative history. In 1927, Owen Henderson, a legislator from Durham and Registrar of the University of New Hampshire, sponsored successful legislation to study the possibility of constructing a bridge "near the site of the old Piscataqua Bridge, so called, at the eastern terminus of the First New Hampshire Turnpike between the towns of Durham and Newington." According to Henderson, his proposal was prompted by the "growing demand for cutting down time and distance between metropolitan areas." In particular, he wanted to "restore [Durham] to its old time position on the shortest and most direct route from Concord to the Sea at Portsmouth" (Henderson ND:79). His hope was to reestablish the route of the 1st New Hampshire turnpike which connected Portsmouth and the Merrimack Valley (Henderson 1936:27).

The Highway Department reported back favorably on February 19, 1929. It had taken borings along the old bridge route and found that the bottom between Newington and Goat Island was solid rock while that between Goat Island and the Durham shore had a layer of soil varying between 6' and 20'. The main proposal was for a steel and concrete bridge with "four 350 foot fixed spans; one 400 foot fixed span and one 140 foot hand operated swing span. It also includes two 100 foot approach spans" ([NH] Highway Department 1929). The Highway Department also presented an alternate design for the channel between Goat Island and Durham consisting of a pile trestle bridge and steel draw span on a concrete pivot pier.

With a favorable report in his pocket, Henderson introduced legislation that called for construction of the bridge. The legislation, although not successful as drafted, had a number of important features that were to influence later successful legislation. His bill specified the then novel concept that the bridge would be "self-liquidating" or pay for itself. The idea was that it would be financed by bonds that would be paid off through tolls paid by bridge users. This kind of financing was novel in New Hampshire and was somewhat controversial given the recent movement to do away with tolls and "free" the bridges. The experience of other states (particularly around New York and New Jersey) especially the Holland Tunnel, where the cost of construction was covered by tolls was influential in convincing fiscally conservative New Hampshire to adopt this method of financing (*Manchester Union,* November 17, 1930).

Another important component of the bill was the inclusion of the construction of 10.25 miles of concrete highways leading to the bridge that would also be paid for out of the toll. This was added at the request of New Hampshire Highway Commissioner Frederick Everett. Henderson later wrote

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[8] State Highway maps dating as late as 1937 show what is now Route 4 as Alternate Route 4, with Route 4 itself taking the Dover/Barrington route.

that he didn't favor "loading the bill down" with this $410,000 expense, but went along with it to gain Everett's support for the measure (Henderson ND:5). Henderson's willingness to incorporate the Highway Department's agenda corresponded to a basic shift around this time in how highway projects were implemented. Historically, with little statewide oversight, individual state legislators pushed "special" road bills in their own district. At this time however, the Highway Department began to assert its role in coming up with a more systematic planning program that assessed the highway needs of the entire state and appropriated funds based on these needs (*Manchester Union,* Feb. 8, 1933).

A final important feature of the bill was its cost. The total price of the bridge package was $1 Million. This gave rise to the bridge's unofficial name, the "Million Dollar Bridge."[9] The cost of the bridge created one major vein of criticism, especially given the dire, depression-era economic conditions. It was called "a mad orgy of extravagance" by one Representative from Farmington (*Concord Monitor* ND).

With the size of the price tag and the fact that a $8,000,000 road bond issue was also being funded that session, the bridge legislation was put off to the next session. Instead, the legislature passed Chapter 272, Laws of 1929, authorizing the Governor to appoint a three-person committee to determine "the feasibility and adaptability of the site and ascertain the cost of such a bridge."

The committee established by the 1929 legislation held hearings on the bridge in 1930. The heated nature of these hearings provided a taste of the strong opposition to the bridge that was to come from the residents and business owners of Dover. Despite this opposition, the committee reported favorably to the legislature in late 1930. Their report included a plan for a bridge consisting of "a series of steel trusses and girders supported by concrete masonry piers." The committee estimated the cost of the bridge to be $750,000 with a total project cost of $1,150,000. They also endorsed the method of financing; they recommended the sale of bonds to cover the cost of the project, which was to be repaid through a 15-cent automobile toll.

Based upon this report, House Bill # 23 was introduced. At the same time, representatives from Dover introduced legislation to purchase the B & M [Dover Point] railroad bridge at a cost of $250,000. This legislation would assure that if the bridge at Fox Point was constructed, the railroad bridge would be maintained by the State. This was necessary because the B&M had plans to abandon the line that used the bridge. In response to heavy lobbying by the railroad to have their bridge purchased by the state, and to increase support for the new bridge, Henderson agreed to combine the two bills (Henderson ND:23). The legislation also specified that in the event of the "discontinuance" of the B & M Bridge, a new bridge would be built over the Bellamy River to take traffic that would have used the B & M Bridge to the new Fox Point bridge. After significant political maneuvering, the bill eventually passed in both the House and Senate and was approved by Governor John Winant on May 7, 1931. The Governor, in a controversial move, signed the bill but stated that it was with the understanding that he would further investigate the project (Henderson 1936:116). Thus yet a third study was authorized, and later in May, the Governor engaged the services of Fay, Spofford & Thorndike, an engineering firm based in Boston, to review all previous studies and make recommendations on the location, design and construction of the new bridge.[10]

In making their recommendations for the bridge across Little Bay, the firm apparently was not limited to the location specified in the legislation; they included sites at Fox Point and those nearer

[9] Although items were later added and subtracted from the proposal, the cost for the project remained roughly the same and thus the name, too stuck.

[10] For more information on FS& T and see biographical section later in the form.

the B & M railroad bridge. They submitted their report on September 12, 1931, with a supplemental report, covering the cost of approach roads, on September 23. They evaluated three possibilities: 1) the Fox Point location discussed in the legislation; 2) a new site at Dover Point near the railroad bridge site (to be accompanied by a bridge across the Bellamy River to allow traffic from Durham to use the new bridge); and 3) the construction of a roadway on a dike or dam across Little Bay at or near the Fox Point site. Based largely on an analysis of the existing traffic patterns in the area, and the "detour" mileage involved in the two locations (and taking into account the poor condition of the existing bridge at Dover Point) the firm endorsed the Dover Point scheme as saving roughly $225,000 (Fay, Spofford and Thorndyke 1931: 133, 138). They nixed the idea of a dike, concluding that it would add an addition $900,000 to the cost of the project for advantages that were "intangible" (Henderson 1936:120).[11]

Based on the recommendation of the report, a new bill was introduced to the legislature on January 24, 1933, placing the bridge "in Newington within one mile south of the existing Dover Point Toll Bridge thence to and across Little Bay at a location within one-quarter mile of the existing Dover Point toll Bridge..." Oren Henderson, the chief proponent of the Fox Point route, threw his support to the new legislation. He conditioned his support on the Highway Department's agreement that the timber trestle bridge at the Bellamy River, be upgraded to a more substantial and attractive structure. The legislation also specified that the approach highways would not be paid for out of the appropriation but would instead be funded from regular highway funds. With this cost saving measure, an appropriation of $1,100,000 ($275,000 for the purchase of the B & M Bridge and $825,000 for the construction of the two bridges) was still possible. The Governor signed the legislation on April 7, 1933. Towards the end of 1933, Public Works administration money also became available and on September 8, 1933, the state received a federal (Public Works Administration) grant of $220,000 to help finance the project. This money may have gone toward the highway construction associated with the project.[12]

The "Million Dollar Bridge" was one of the more expensive projects that the state had funded and there was some amount of controversy about spending so much in the middle of such hard economic times. However, by the time the bridge was under construction, it provided work for many unemployed men. During the eight-year period between when the bill was first introduced and when it was signed into law, there were major shifts in how both the country and state were dealing with economic issues. Early on in the Depression, there was a conservative approach to expenditures, but by 1933, Governor Winant and newly elected President Roosevelt both favored funding for large public works projects that would get the unemployed back to work. The General Sullivan project with the accompanying road construction was considered an excellent unemployment measure, because roughly half of the $1,100,000 project cost went for labor (*Manchester Union* March 7, 1933). In the end, around 600 men were employed on the project.

On April 11, 1933, four days after the legislation went through, Fay, Spofford was hired to prepare the design of both the Dover Point and Bellamy River Bridges. However, there was one final hurdle. On May 8, the War Department held a hearing on the bridge's design, which did not have a draw

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[11] Robert H. Marin, editor of the *Newmarket Advertiser* was the main force behind the dike idea which would have turned Great Bay into a constant-level freshwater lake.

[12] An additional $50,000 came in 1935 for work on the Bellamy River Bridge (*Manchester Union* March 15, 1935). It is not clear how PWA funding was utilized in the project. According to Henderson, the highway work was carried on as a "work relief project" (Henderson 1936:164). However, a sign on the bridge itself identifies it as "U.S. Public Works Project Docket No. 752." Public Works Administration files, which are housed at the National Archives and Records Administration [NARA] in College Park, Maryland, no longer exist for this project.

span. Most in the audience, which included individuals representing shipping interests and pleasure craft owners, spoke against the proposal, fearing that without a draw the bridge would negatively impact marine activities. They urged the War Department to require a draw span similar to that on the B & M Bridge. The War Department compromised, deciding that no draw span would be required if the bridge could be built with a clearance of 50' above mean low tide (Henderson 1936:160). The Bridge Commission met on May 16 and agreed to alter the plans to accommodate the War Department's requirement. The new design raised the center span 10' giving a clearance of 50' at high water mark. This meant that the design had to incorporate a steeper grade on both approaches (*Manchester Union*, May 16, 1933). By June 8, the firm had plans ready for bidding on the substructure of the bridge. By July 27, plans were available for the superstructure. Plans followed for the Bellamy River [later Scammell] Bridge on April 13, 1934.

Crandall Engineering Company of Cambridge, Massachusetts was awarded the contract for the substructure.[13] Their bid was for $238,000 for a 1935 completion date and a price of $244,444 for completion before Dec. 31, 1934 (*Fosters Daily Democrat* June 9, 1933). The superstructure, with an estimated weight of 3,700,000 pounds of carbon steel, was awarded to the Lackawanna Steel Construction Company (LSC) of Buffalo, NY on August 24, 1933 for $228,050[14]. The work was to be completed by June 30, 1934, with a $100 per day bonus or penalty clause for each day the superstructure and deck was completed prior to, or later than, the specified date.

<u>Analytical Solution and Methods of Stress Analysis for the General Sullivan Bridge</u>

Fay, Spofford's design employed three continuous spans over the main channel at Little Bay. Their design was based upon three factors: aesthetics, an estimated cost savings in steel, and a desire to keep the channel open during erection. The quantity of steel required in a continuous truss, especially a long span highway bridge where the dead load is large in comparison to the live load, is less because the load under every member of the truss assists in resisting the various loads that are placed on the structure. Deflections, even with the smaller amount of steel, are also less in a continuous truss when compared to a simple truss or a cantilever truss. As described by Spofford in his article on the Lake Champlain Bridge, it is likely that the significant cost savings, the improved appearance, the reduction in the number of expansion joints and the ease of construction, all lead to the selected design (Spofford 1933). The only drawback to the continuous design was the additional amount of computational time required to design the continuous spans.

In the end, the Dover Point Bridge design had much in common with the Lake Champlain Bridge. Although the area to be spanned was shorter, Fay, Spofford, decided to use the same Warren Truss pattern with the same type of truss supports at the piers as in their Crown Point Bridge. The engineers took into consideration the trade off between the number of piers in the water and the economic span length of various bridge styles and materials. The height and width of the required clearance under that part of the bridge over the main shipping channels was a major factor. Finally, the elevation of the ground on both sides of the bridge, taken in conjunction with the required clearance under the bridge, dictated the profile of the roadway. Given all of these factors, as well as cost, Fay, Spofford, arrived at the bridge's asymmetric design.

The bridge was designed using an AASHO (now AASHTO) H15 loading requiring a live load of 610 #/square foot on the roadway and 200#/square foot on the sidewalks in addition to concentrated loads of 16,900 # for moment and 24,500 # for shear placed to cause the maximum stresses. Carbon

[13] Biographical information on the firm can be found at the end of this section.
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steel with an allowable stress of 16,000 psi in tension for live load and 24,500 psi for dead load was utilized throughout the superstructure.

Span #1 and span #7 were simply supported and the trusses were statically determinate and member forces under the design loads could be easily determined by calculation or graphical statics. Span #7 was designed as a simply supported truss due to the War Department's requirement that one span should be able to be converted to a lift span if shipping should warrant a greater clearance in the future. Spans #2 and #3 as well as spans #8 and #9 were identical and continuous over pier #2 and Pier #8. With a pin at pier #1, a roller at pier #3 and a rocker at pier #2, spans #2 and #3 were statically indeterminate to the first degree. This meant that there were four unknown reaction components and only three equations of equilibrium available to determine the unknown reaction components from which, combined with the live and dead loading, the truss member forces could be determined and members sized accordingly.

The analytical methods used to analyze stresses for the General Sullivan Bridge were not new or sophisticated, but were apparently chosen due to their familiarity, ease in checking, and suitability to be divided among a staff of calculators. According to Spofford, the Method of Least Work was used to calculate the stresses in the continuous trusses of the bridge and he explains that: "A preliminary design was first made using reactions as determined by the 'Three Moment Equation' this was followed by a more accurate determination of the stresses applying the least work principle and revising the section areas accordingly (Spofford 1935:10)." There was nothing particularly novel or significant about this mathematical approach to the problem at the time, it was one of the oldest mathematical methods for solving elastic theory problems. Spofford and his "calculators" who performed the laborious and repetitive calculations used the same methods for the design of the Lake Champlain Bridge six years earlier. In discussing the Lake Champlain project, Professor Robert Abbett questioned the immense labor of using the method of least work, when better methods were available (Abbett 1933: 655). Spofford replied that he found the least work method preferable when the computations can be divided among several staff members.

The "three moment equation" originated with the French engineer Clapeyron who studied a continuous beam with three supports. The load on the center support depends on the length of the beam, but also on its elasticity. Clapeyron discovered a mathematical relationship between the bending moments (three) at each support based on the loads on the beam between each support. He published his theorem in 1857 and it has since been known as Clapeyron's Theorem of Three Moments (Westergaard 1930:232). The reactions on continuous girders can be accurately determined using the theorem if the entire beam is of constant section and material (constant moments of inertia and modulus of elasticity), if not then the method requires a series of repeated calculations in which the reactions are approximated and results adjusted to obtain the desired accuracy (Spofford 1937: 2-3).

The Italian engineer Alberto Castigliano (1847-1884) presented the method of least work theory in his book "Theorie de l'equilibre des systemes elastiques et ses applications" published in Turin in 1879. The first to explain Castigliano's theories in English was MIT (later Harvard) professor George F. Swain in 1883 (Swain 1883). It was not until 1919 that Castigliano's book was translated in full into English by British engineer E. C. Andrews under the title *Stresses in Elastic Structu*res (Andrews 1919).

The first comprehensive presentation of the method of least work in the U.S. appears to be an 1891 article by William Cain who gave this introduction to the subject:

> The method is found to be of very general application to all structures in which the laws of elasticity have to be considered in finding the stresses; as in every kind of beam or arch, trusses of any shape with superfluous members and all systems where there is a continuity in the members or where there is not free play at the joints, as in nearly all roof or bridge trusses. It further offers an exact method by which we can ascertain the limit of error made in our ordinary approximate computations (which apply only to articulated systems, free to move at all the joints), and thus exposes some of the unknown errors which are usually included in our "factor of safety," though it has more appropriately been termed our "factor of ignorance" (Cain 1891: 264+).

Probably the best simple introduction to the principle and application of the method of least work is that given by British engineer, Harold M. Martin in 1895:

> Every metallic or wooden structure is elastic, and constitutes a spring. If a spring is loaded by a weight, it elongates, and a certain amount of work is done in this elongation. This work is stored in the spring in the form of potential energy, and can be reconverted into mechanical work, as is commonly done in clocks and watches. The stiffer the spring the less it is deformed by a given weight, and hence less work is stored in a stiff spring loaded with a 1-lb. weight than in a light one loaded by the same weight. Thus if 1 ton is hung from a steel bar of 2 square inches in section, less work is done in deforming the bar than if it was hung on a steel bar of the same length and of 1 square inch section. If a weight lies on a platform supported by four legs of elastic material, work will be done in deforming the platform and compressing the legs.
>
> If there had been only three legs, the ordinary principles of statics would suffice to determine the weight taken by each leg, which is then quite independent of the comparative stiffness of the legs and the platform. When, however, we have more than three legs, these statical principles no longer suffice, and to determine how much of the weight is carried by each leg it is necessary to introduce other considerations. The one great principle to which such problems can be reduced is known in dynamics as that of least action, and in such problems as we have before us as that of "least work." That is to say that the work stored in an elastic system in stable equilibrium is always the smallest possible (Martin 1895).

Martin goes on to describe in simple mathematical terms how to solve for the load carried by each leg with a given weight located at a certain place on the table, and then proceeds into analyzing increasingly complicated frames.

Through the 1890s up to the mid-1930s, a great number of important articles and textbooks were published on the subject of statically indeterminate structures, several of which are discussed below. For a broader review of the body of work on the subject, the reader is referred to two excellent historical summaries on the subject.[15]

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[15] For an excellent history and annotated bibliography on the analysis of indeterminate structures see, John I. Parcel and George A. Maney, *An Elementary Treatise on Statically Indeterminate Stresses* (New York: John Wiley & Sons 1926); also

A paper given in 1899 by Frank E. Cilley discussed the futility of hoping to analyze indeterminate structures with an exactness and provoked contrary discussion by such majors as Lindenthal and Swiss professor C.W. Ritter. Lindenthal called the paper "a contribution to the old controversy as to whether or not statically determinate structures are superior to statically indeterminate ones, and is a scholarly attempt on the affirmative side of the equation (Cilley 1900: 353-443)." Cilley's paper was a brilliant thesis that argued with sophisticated mathematical reasoning that a determinate structure can and should supplant an indeterminate one in every case, and that structural redundancy therefore equals structural waste. This work had a lasting effect in dividing American engineers into two camps, and as noted above, it was not until Lindenthal and several other leaders built major continuous trusses, and new minds reasoned their economic validity, that the merit of indeterminate bridges became generally recognized.[16]

In 1905 Professor Isami Hiroi of Tokyo Imperial University wrote the first textbook in English (published in the U.S by Van Nostrand) on the use of the method of least work to solve for secondary stresses in bridge trusses (Hiroi 1905). Carl Grimm devoted a chapter to using the method of least work in his 1908 book Secondary Stresses in Bridge Trusses, as well as chapters on the four other leading methods for solving secondary stresses: Manderla method, Muller-Breslau method, Ritter method, and Maxwell-Mohr method (Grimm 1908).

In 1911, the two leading college structural engineering textbook authors – Johnson, Bryan & Turneaure and Merriman & Jacoby – came out with new editions of their multi-volume treatises that included sections on the complete application of method of least work (Johnson, Bryan and Turneaure 1911; Merriman and Jacoby 1911). Two more textbooks, C.M. Spofford's *Theory of Structures* (1911) and *Theory of Framed Structures* (1922) by C.A. Ellis both contained sections on indeterminate structures and the method of least work.

In 1926, John I. Parcel and George A. Maney published the An Elementary Treatise on Statically Indeterminate Stresses (Parcel and Maney 1926). This became arguably the leading text on the subject for decades, coming out in three editions until it was complete revised with a new title and coauthor in 1955 as Analysis of Statically Indeterminate Structures (Parcel and Moorman 1955). Parcel was professor of structural engineering at the University of Minnesota and later a partner in the firm of Sverdrup & Parcel. He called Johnson, Bryan and Turneaure's 1911 *Modern Framed Structures* "the best and most comprehensive treatment of statically indeterminate stresses in the English language" (Parcel and Maney 1926: 359).

The first major American contribution to the analysis of statically indeterminate structures was made by Hardy Cross in 1930 when he described a new method for analyzing building frames that became known as the moment distribution method. When published in the ASCE Transactions in 1932, it was followed by 146 pages of discussion from thirty-eight commentators, possibly a record. "Cross was immediately hailed as the man who had solved one of the knottiest problems in structural analysis" (Eaton 2001). His method was later called "probably the most notable advance in structural analysis during the twentieth century" (Shermer 1957:188). The Cross method was readily applied to solving secondary stresses in trusses, as demonstrated by Professor F.P. Witmer, head of

see, H. M. Westergaard, "One Hundred Fifty Years Advance in Structural Analysis," *Transactions of the American Society of Civil Engineers* 94 (1930): 226-246.

[16] Another excellent paper and discussion of the methods of analysis of indeterminate structures including Cilley's paper is: Hardy Cross, "The Relation of Analysis to Structural Design," *Transactions of the American Society of Civil Engineers* 101 (1936): 1363-1408.

the engineering department at the University of Pennsylvania, who applied it to the same 150' Warren truss example as was used by von Abo in his landmark 1926 paper. Witmer completed the analysis in only six hours, and claimed that the method "will prove to be the simplest and most expeditious method yet advanced for this purpose" (Witmer 1932: 132-133). Had FS&T used the Cross method to solve the stresses of the General Sullivan Bridge, that would have been a first. Instead, the first to apply the moment distribution method to a continuous truss appears to be Truman P. Young, a structural engineer from Ohio, who designed a three-span continuous arched truss and published his procedure in 1936 (Young 1936: 382-383).

As discussed above, in order to ensure the trusses were acting as designed Fay, Spofford, inserted a jack and proving ring system at each reaction component that was determined by the Least Work Method. This required a pair of jacks and proving rings acting in vertical directions at pier #3 and pier #6. The jacks pushed against the proving rings, which were calibrated to read the force being transmitted through to the truss, until the force matched the value calculated. With these values locked into the system, Fay, Spofford could be confident that the truss members were acting as their analytical model and that each member had been properly sized.

Construction and Later History

A host of unfavorable environmental conditions severely complicated construction of the General Sullivan Bridge. These included the long distance to span, extremely fast tidal currents in the channel, a water depth at the lowest point of approximately 37' at low tide, and a rock bottom covered with 4' to 10' of clay, sand and gravel which was difficult to set falsework in (*Engineering New Record* 1934B: 358, Archibald 1935).

Work by Crandall Engineering on the foundation began July 27, 1933. The specifications called for the use of cofferdams, which would permit excavation of the soil down to bedrock and the pumping out of water so the concrete could be poured in the dry (up to elevation 92.0). The contractor built temporary wooden trestles from the abutment out to piers #1, #2, #3 on the west and from the abutment to piers #8, and #7 on the east. Given the strong currents, pile driving for the coffer dams could be done only during slack tide. Sheet piling was driven and wales placed inside, as the excavation inside the cofferdam proceeded towards bedrock. After they pumped the water out, the concrete bases were formed and poured. From that level up to 117.0 on the west, the granite blocking, backed with concrete, was placed on the five piers (*Engineering News Record* 1934B:388)

Piers #4, #5, #6 however, proved much more troublesome due to the rapid currents through that portion of the channel. Crandall started Pier #5 by driving clusters of wooden piles around the pier; these washed out almost immediately. They then drove lines of wooden piling around the pier, but these too were washed out by the current. They then decided to drive steel sheet piles. These were supported from lighters anchored by steel cables to deadmen and from anchorages on the shore. The flexibility of this method, however, made it difficult to dewater the interior. Working with Fay, Spofford, the specifications were modified to allow some concrete to be poured using tremie concrete until the water could be pumped out and the remainder of the concrete poured in the dry and masonry placed up to the design level. Similar steps were taken in placing the other two piers. Fay, Spofford required that large rip-rap boulders be placed around these piers to minimize possible scour below the tremie concrete. Despite these setbacks and difficult working conditions, Crandall was able to turn the bridge over to the steel erector on January 23, 1934, one month after its December 31, 1933, contract date (*Engineering News Record* 1934A:389).

Lackawanna's work on the superstructure, already a challenging proposition, because of length of the bridge, was made much more difficult by extreme weather conditions. It received its first shipment of steel the week of January 16, 1934, and, using the falsework left by Crandall, began erection shortly thereafter. Steel for the structure was fabricated in Buffalo and shipped by rail via the B&M railroad to the bridge site. Lackawanna began work on spans 1, 2, 3, and 9 using the trestle built by Crandall Engineering that they had upgraded. Although initially there were no problems, spring breakup in the bay however caused a significant setback. Steel was being placed on span 8 when, on March 8, "monster cakes of ice" moving at an estimated twenty miles an hour on an outgoing tide destroyed pilings on a 40' length of the old bridge, the Crandall trestle and a portion of the new truss (*Fosters Daily Democrat* 1934A:1). A number of conditions conspired to create extreme conditions. Cold temperatures and heavy precipitation in November through February created deep ice on Great Bay, which when combined with extremely high tides and strong winds, all contributed to the problem (U.S. Department of Commerce 1970). On March 12, another "huge" cake of ice struck a pier on the new bridge, but apparently did little damage (*Fosters Daily Democrat* 1934B). By around March 14, construction of the new bridge stopped due to a lack of steel. The steel, located at Dover Point, could not be moved via the old bridge (for fear of further damaging it), nor could it be hauled on the highways (because of its size and weight) or transported via boat, so construction stopped (*Fosters Daily Democrat* 1934C:1). Overall, however, damage to the new bridge itself from the incident was less than could be expected. Because the truss had been designed as a continuous truss, when the trestle was destroyed much of the truss work acted as a cantilever with Span 9 being the anchor span. On April 9 when work resumed, the contractor placed a temporary steel bent near mid span and erected the remainder of the span by cantilever methods moving from east to west to pier #7.

Although Lackawanna had originally planned to erect span #7 on barges anchored along span #8, the success of erecting span #8 by cantilever methods convinced Lackawanna to erect it using another central pile bent. Since the span was simply supported they had to make a temporary tie back to span #8. The truss was connected to the pier by a pin so all that was needed was a tension tie between the top chords of the two trusses. The process began by building out, by cantilever methods, to the point where the mid span bent was to be placed. The bent was then placed off the end of the cantilever and the truss extended by the same cantilever methods to pier #6.

Steelwork was now in place, except for the continuous spans #4, #5, and #6. The contractor determined that erection of spans #4 and #6 would be most effective if the spans were built on barges anchored along the completed span #3 and floated into place at high tide and set on piers #3 and #4 for span #4 and piers #5 and #6 for span #6. These spans were erected and floated into place without problem. The 275' long center span, #5, was placed by cantilever methods from both ends to meet in the middle of the span since it was believed that it would be extremely costly to build on falsework and be in constant danger of destruction by the rapid currents through this portion of the bay. All steel for these spans was shipped via the B & M line and off loaded to barges on the easterly end of the bridge. Derricks, running on the completed deck structure of the bridge, lifted members from these barges and set them in place.

In order to have some control of the height of the truss when the two ends of the cantilever were approaching one another, Lackawanna followed a procedure similar to that used on the Lake Champlain Bridge. Under the process, the outer ends of the continuous spans were held lower than their plan elevation so the ends of the cantilever would be higher than plan. As the outer ends were jacked upwards, the center ends of the trusses would drop until the top and bottom chords arrived at a level where the connecting members could be placed. After shoes at piers 4 and 6 were at the proper level, and truss connections were made at mid span, shims were placed under them to maintain at the design elevation."(*Engineering News Record* 1934A:390).

With the span now continuous over piers x3, 4, 5 and 6 Fay, Spofford, in order to ensure that the truss would act the way it was designed, inserted pairs of jacks and proving rings at piers #4 and #6 oriented in the vertical direction. The jacks were extended, loading the proving rings until the design value of reaction was achieved. At that point, additional shims were placed locking in the reaction values, which in turn ensured the truss was acting as designed. After this, all joints were fully riveted and the superstructure completed. The final weight of steel in the superstructure was 3,689,068 pounds or just below the amount estimated in the contract documents.

The concrete deck was placed starting from pier #4 westward and pier #6 eastward until the abutments were reached. Expansion and contraction deck joints were placed at piers on the west side of pier #1, at piers #3 and #6 as well as on the east side of pier #7 each of which contained roller supports. The abutments had been concreted at the same time the piers were being placed. Concreting of the middle span was from the center of the truss towards piers #4 and #6. The deck was an 8½" thick reinforced concrete deck placed in two layers. The main, or structural layer was the reinforced layer and was 7" thick. Wooden forms were set upon the stringers of the bridge. Welded mats of main steel, temperature steel and the transverse trussing members were prefabricated into units running the full width of the bridge and seven feet wide. The 1½" thick wearing surface was placed shortly after, prior to initial setting of, the main layer so that proper bonding between the two layers was achieved.

By early summer it was clear that Lackawanna was going to miss its contract date by several months even though it continued to assure the state they would be ready for an opening in August. The last phases of the project were completed in late August when the railings were placed and the final coat of paint was applied. The bridge was completed and ready for opening on September 5, 1935, or a little more than a month late.[17]

A dedication ceremony was held for the bridge (and for the not-yet-completed Bellamy River Bridge) on September 5, 1934. Representatives from Newington, Dover and Durham (mostly the children and grandchildren of politicians) cut the three ribbons stretched across the middle of the span. Then the assembled dignitaries moved to the Dover Shore for speeches. Oren Henderson gave an historical talk, Charles Spofford talked about the design and construction of the bridge and Sims Frink, grandson of Cyrus Frink one of the builders of the first Piscataqua Bridge, gave a history of the area (*Foster's Daily Democrat* September 5, 1935). The Governor, in accepting the bridge, noted, "This great span which in stormy times carries us over rough water and heavy weather, shall be a symbol of the building up of faith. In hard times and hardship we have the faith to believe that we shall carry the banner ever onward as a reflection of all that God made beautiful and the character of a great people" (*Portsmouth Herald*, September 5, 1935). After the speeches, the dignitaries traveled to the Cohecho Country Club in Dover for a dinner and following that there was a parade.

Soon after the bridge was completed, Oren Henderson, the primary backer of the construction of the bridge submitted legislation to name the bridge after General John Sullivan, a Revolutionary War hero from Durham. Henderson testified for the name before the Public Improvement Committee of the New Hampshire House in early 1935 emphasizing the fact that Sullivan's home and grave (on the Oyster River) were near and that Sullivan traveled Little Bay and the site of the new bridge to reach Portsmouth.(*Manchester Union,* February 1, 1935)[18] After the bill to rename the bridge

[17] The superstructure was to be completed and the bridge opened by June 30, 1935. The $100 day penalty would be assessed to Lackawanna Steel for any delay after that date.

[18] John Sullivan was one of the New Hampshire delegates to the Continental Congress in Philadelphia in 1774 and 1775, and a Brigadier General in the Continental Army where he served with General George Washington at the battles of Boston, Long Island, Trenton, Princeton, Brandywine, Germantown and spent the winter of 1777-78 in Valley Forge. After the war,

passed the House on January 31, 1935, it went through the Senate, and was signed by the Governor shortly after (Henderson 1936:206).

By 1936, local and state officials began looking into the possibility of beautifying the approaches to the bridge, which on the Dover side included various farm uses considered unsuitable for a setting for the bridge. At that time, New Hampshire Governor Henry Styles Bridges appointed a committee to study the feasibility of acquiring the land in Dover and Newington. With a favorable finding from the committee, in 1937, the State Legislature passed legislation authorizing the Governor and Executive Council to secure land adjacent to both the Sullivan and Scammell Bridges "for park and recreation areas" and appropriated $40,000 to acquire land and establish the parks. In 1940 after the land was assembled $5,000 was expended for "grading and beautification of approaches" to the bridges. Although the Dover side was later improved and became known as Hilton Park, the Newington land was never developed.

It took fifteen years for the Sullivan Bridge to pay for itself through tolls. In an article reporting on the "freeing ceremony" that was held at Hilton Park in 1949, the *Portsmouth Herald* reported that the revenue from the bridge paid not only for the construction of the Sullivan and Scammell bridges but also for the approaches to the bridge and "the beautiful Hilton Park [which was] constructed from bond issue funds liquidated by income from the bridge" (*Portsmouth Herald*, October 31, 1949).

After the completion of the bridge, the main routes from Portsmouth northward and westward into the state became fixed for the years to come. The bridge was incorporated into NH Route 16 (Spaulding Turnpike) and Route 4. Clearly, at the time the General Sullivan was being planned, the concept of a road following the route that the Spaulding Turnpike eventually took was already contemplated.[19] Constructed beginning in 1953, the Spaulding Turnpike was to become the primary route north from the seacoast area to the White Mountains and Lakes Region. Its route was planned to utilize the General Sullivan Bridge. With increases in traffic, however, a new bridge over Little Bay became necessary. Built slightly to the east of the General Sullivan in 1966, northbound Spaulding Turnpike/Route 4 traffic used the Sullivan and southbound traffic used the new bridge. In 1984, additional lanes were added to the replacement bridge, and northbound traffic moved to the new lanes and the General Sullivan Bridge was mothballed.

Background of the Bridge's Engineers and Contractors

Fay, Spofford & Thorndike

The engineering consulting firm of Fay, Spofford & Thorndike was established on July 1, 1914, by Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike. All three men were classmates and graduates of the Massachusetts Institute of Technology civil engineering program and studied under George F. Swain. Fay and Spofford graduated together in 1893, Thorndike graduated in 1895 and they remained in contact thereafter. Fay and Thorndike worked together as engineers for the City of Boston for over fifteen years, and Thorndike taught occasional courses at MIT where Spofford was a full time professor. Together, the firm enjoyed a long and distinguished history in bridge design. The firm's work was varied, and included construction of the Boston Army Base; the engineering for a new town, Mariemont, Ohio; the Bourne and Sagamore Bridges over Cape Cod Canal; and the

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he was active in New Hampshire State politics serving as Attorney General, Speaker of the House, and President of the State in 1786.

[19] "It is understood that if this bridge is built, it will be a great step in a plan to complete a cement highway from Portsmouth to the White Mountains through Dover, Rochester and the Conways to attract tourist traffic into the lake and mountain region (*Foster's Daily Democrat* February 2, 1933).

Lake Champlain Bridge. Later work in New Hampshire included work on portions of the Everett Turnpike and two Manchester bridges over the Merrimack River.

Frederic Harold Fay –FS&T

Frederic Harold Fay was born in Marlboro, Massachusetts, on July 5, 1872 and died at his home in Dorchester, Massachusetts, June 5, 1944. Following completion of his Bachelor's degree at MIT he was accepted to the school's new graduate program. In 1894, he became the first person to receive a Master of Science in Civil Engineering from MIT. Fay worked briefly for Boston Bridge Works and then in 1895 joined the engineering department of the City of Boston where he rose to the position of Engineer in Charge, Boston Bridge and Ferry Division, Department of Public Works.

In 1909, Fay authored a paper with Spofford and another city engineer, J.C. Moses, on the reconstruction of the Boylston Street Bridge over the Boston and Albany Railroad, a major undertaking for the city (Fay, Spofford and Moses 1909: 234-268).

He resigned from the City in 1914 to join in partnership with Spofford and Thorndike. Fay took an interest in large scale planning projects and became the firm's expert in that field. Among his many projects, one of the largest was the design of the $25 million Boston Army Supply base at South Boston built 1918 to 1919. He was chairman of the Boston Planning Commission from 1922 to 1939, a member of the State Planning Board, and a president of the Boston Society of Civil Engineers (*Transactions of the American Society of Civil Engineers* 1945:1691-1694; Downs 1941:560; *New York Times* 1944: 19). In 1948, to commemorate its 100-year anniversary, the society asked several of its leading members to write articles on the outstanding contributions to engineering made by former members. Spofford was asked to write about those who contributed the most to the field of structural engineering and chose three: George F. Swain (1857-1931), Joseph R. Worcester (1860-1943) and Frederick H. Fay (1872-1944) (Spofford 1948:337-342). Spofford pointed to the Lake Champlain Bridges (FS&T also designed the Rouses Point Bridge over the lake in 1937), his port and maritime studies and designs, and his grade crossing elimination project designs including the massive Syracuse project completed by the New York Central Railroad (Spofford 1948: 342).

Charles Milton Spofford –FS&T

Charles Milton Spofford was born in Georgetown, Massachusetts, on September 28, 1871 and died in Newton, Massachusetts, July 2, 1963 at the age of 91 (*Civil Engineering* 1963:60; Downs 1941:1303). Like Fay, Spofford also did post-graduate studies in civil engineering from 1893-1894, but it is not clear if he completed his Masters degree. He co-authored a thesis in 1893 for his B.Sc. degree entitled "An investigation into the action of elliptical car springs" (Bryant and Spofford 1893). Spofford worked for the Phoenix Bridge Company from 1895 to 1899, but only summers from 1897-1899 when he taught in the MIT engineering program as an assistant instructor during the school year. He taught at MIT full time as an assistant professor from 1903 to 1905, then accepted a professorship in civil engineering at Polytechnic Institute of Brooklyn from 1905 until 1909. In that year he returned to MIT to accept the position of Hayward Professor of Civil Engineering where he remained until his retirement in 1954.

Spofford published a college engineering textbook in 1911 entitled "The Theory of Structures" which became a standard and was republished in four editions, the last being in 1939 (Spofford 1911 et seq). He was not a prolific writer or engineering theorist however. His only other major work was his 1937 textbook *The Theory of Continuous Structures and Arches*, which joined several others in an increasingly crowded field. He wrote about ten articles for journals. Useful contributions are the Boylson Bridge article he wrote with Fay, a detailed investigation of highway bridge floor types, a historical piece on Thaddeus Hyatt – an early American inventor of reinforced concrete, a method for the division of bridge costs between street railways and cities, and his report on the use of proving rings that resulted from his work on the General Sullivan Bridge (Spofford 1915:727-754; Spofford 1913:211-217; Spofford 1915; Spofford and Gibbons 1935:446-449). His other half-dozen articles reported on the salient features of important bridge design work done by FS&T, but did not really add materially to the greater body of engineering knowledge.[20] In 1942 he chaired the American Society of Civil Engineers (ASCE) in-house sub-committee that reported on the Tacoma Narrows Bridge collapse (Spofford 1942).

Sturgis Hooper Thorndike FS&T

Sturgis Hooper Thorndike was born June 11, 1868 in Beverly, Massachusetts. He received a B.A. from Harvard in 1890 and a B.Sc. in civil engineering from MIT in 1895. Following graduation he entered the employ of the City Engineer of Boston where he spent the first eighteen years of his career. His work for the city involved a large amount of bridge design, and in 1906 he was made assistant engineer in charge of bridge design. He had a major role in many of the city's prominent bridges including the Longfellow Bridge over the Charles River to Cambridge. Between 1904 and 1906, he was granted a leave of absence from the City during the school terms to teach engineering courses at MIT. In 1911, he was promoted to Designing Engineer of the Bridge and Ferry Division of the Department of Public Works, but later in the year resigned the position to establish a private consulting practice. In 1914, he formed a consulting partnership with fellow MIT alums Fay and Spofford. Thorndike remained a principal of the firm until his death February 16, 1928, at the age of 60 (*Transactions of the American Society of Civil Engineers* 1929:1910-1912; Downs 1925: 2086).

Howard James Williams –FS&T

Howard James Williams, of Fay, Spofford & Thorndike, served as "assistant engineer in charge of detailed design" on the General Sullivan Bridge project (Spofford 1935: 21). Williams was born in Kingston, Canada, in 1895, received his B.Sc. in civil engineering from Queens College, Kingston, in 1917, and his M.Sc. in engineering from MIT in 1920. He worked for several firms as an engineer on hydropower developments at Niagara Falls, Quebec and Maine until 1926 when he joined FS&T as a senior engineer. He became a partner in 1947 and an officer/director of the firm in 1956. His obituary was not located but he was still with FST in 1964. In addition to his bridge design work, Williams was chiefly responsible for design work on the New Jersey Turnpike and the Port of Portland, Maine (Downs 1925:2282; Downs 1937:1510; Downs 1948:2177; Downs 1954:2646; Downs 1964:2035).

Lackawanna Steel Construction Company, Buffalo, NY

The Lackawanna Steel Construction Company was part of the large, horizontally integrated, Lackawanna Steel Company, also of Buffalo. Lackawanna Steel, originally located in Scranton, Pennsylvania, moved in 1901 to West Seneca, New York, just outside of Buffalo. Bethlehem Steel Company bought out Lackawanna's steel production operations in 1922; however, the Lackawanna Bridge Works continued fabrication work. The name Lackawanna Steel Construction Company appears in the Buffalo City Directories beginning in 1930 throughout the 1930s. The company was located on Hubbard Street in Buffalo, across the railroad tracks from the Empire Bridge Works. In addition to the General Sullivan Bridge, Lackawanna constructed a number of other bridges in New Hampshire in the mid-to-late 1930s. These include: the Scammell Bridge (replaced) which was part of the same project as the General Sullivan (1935); the former Manchester Street Bridge in Concord

[20] In addition to the other articles by Spofford cited elsewhere he wrote: "To Build a Large Bridge Across the Connecticut at Springfield," *Engineering News-Record* (April 22, 1920): 817-818;

(1933); the Holderness-Plymouth Bridge (1934); the Stinson Lake Road Bridge in Rumney (1934); the Connecticut River bridge between Monroe, New Hampshire, and Barnet, Vermont; and a bridge over the Pemigewasset River in Woodstock (1939).

Andrew Peter Ludberg-LSCC

Andrew Peter Ludberg, was employed by the Lackawanna Steel Construction Corporation as Resident Engineer in charge of the steel superstructure on the Little Bay Bridge (Spofford 1935:15). Ludberg was born in 1889 in Ostersund, Sweden, and immigrated to the U.S. when he was 4. He received a B.Sc. in civil engineering from the University of Wisconsin in 1911 and after graduation joined the engineering department of the Chicago, Milwaukee, St. Paul & Pacific Railroad. He worked for the American Bridge Company as a structural draftsman from 1913 to 1921. Between 1921 and 1927, he was associate professor of civil engineering at the University of Idaho (Downs 1925:1299). He briefly returned to American Bridge Company, but soon accepted the position of chief draftsman at the Lackawanna Steel Construction Corporation. Ludberg possessed a "remarkable skill in mathematical analysis and insight into the elastic behavior of structures, especially those of the 'higher' and indeterminate type," and it likely because of those abilities that he was assigned resident engineer on the Little Bay Bridge project (*Transactions of the American Society of Civil Engineers* 1934:1578). On April 11, 1934, during his routine morning inspection of the steel work, Ludberg stepped on an unattached section of concrete formwork on Span 3 and fell to his death. He was the only fatality resulting from the construction of the General Sullivan Bridge (*Transactions of the American Society of Civil Engineers* 1934:1577-1579).

Crandall Engineering Company, Cambridge, MA

The contractors responsible for the substructure of the General Sullivan Bridge traditionally did not work in the field. Crandall Engineering got its start in Rhode Island in the mid-nineteenth century. The Crandall family owned a shipyard in Newport and constructed a marine railway there. The family soon went into the business of constructing dry docks as the Crandall Dry Dock Company. The company moved to Nova Scotia and continued to construct dry docks and marine railways throughout Canada, the eastern seaboard, West Coat, South America and the Philippines. Around the turn of the century, the firm moved to Boston as H.I. Crandall and Son. By this time, almost every East Cost Harbor in the U.S. and Canada had one or more Crandall railway (Crandall Dry Dock ND:2). The Crandall marine railway dry dock proved particularly popular because of its simplicity of operation and minimum manpower requirements. In 1917, the company became known as Crandall Engineering Company. Although thriving during the World War I, the company's business declined severely during the Depression. This is likely the reason for its venturing into a field that it did not have significant experience in, in its construction of the substructure of the General Sullivan. Around the time of the construction of the General Sullivan, the company apparently split up. The Crandall Engineering Company name went to one part of the family, and the rest of the family and many of the key employees at that time founded Crandall Dry Dock Engineers, Inc., which continues in operation today (Crandall Dry Dock ND). [21]

42. Applicable NHDHR Historic Contexts:

84. Automobile highways and culture, 1900-present.

92. Engineering in New Hampshire 1623-present

[21] Crandall's name changes are somewhat complicated. It was Crandall Engineering of Cambridge in 1933, Crandall Dry Dock Engineers in 1935, Codark Engineering in the late 1930s, then Crandall Engineering and Crandall Dry Dock Engineers again in the 1940s or 50s (Schaller 2005).

43. Architectural Description and Comparative Evaluation:

The 1585 ' long General Sullivan Bridge is a highway bridge that crosses Little Bay at the Piscataqua River. The bridge is currently in use only for pedestrians and bicycles. When in use, the bridge was approached by a two-lane concrete road, the Dover approach of which was widened to accommodate a tollhouse. The vertical clearance over the bridge deck is 18'-½". The depth of Little Bay under the bridge at mean tide is 32 ', and the bridge is 17 ' above mean high tide. The width of the channel is 1525 '.

The bridge is a nine-span truss bridge of varying span lengths with short approach spans at each end. Beginning at the Dover Point end of the bridge and moving easterly, the structure is as follows:

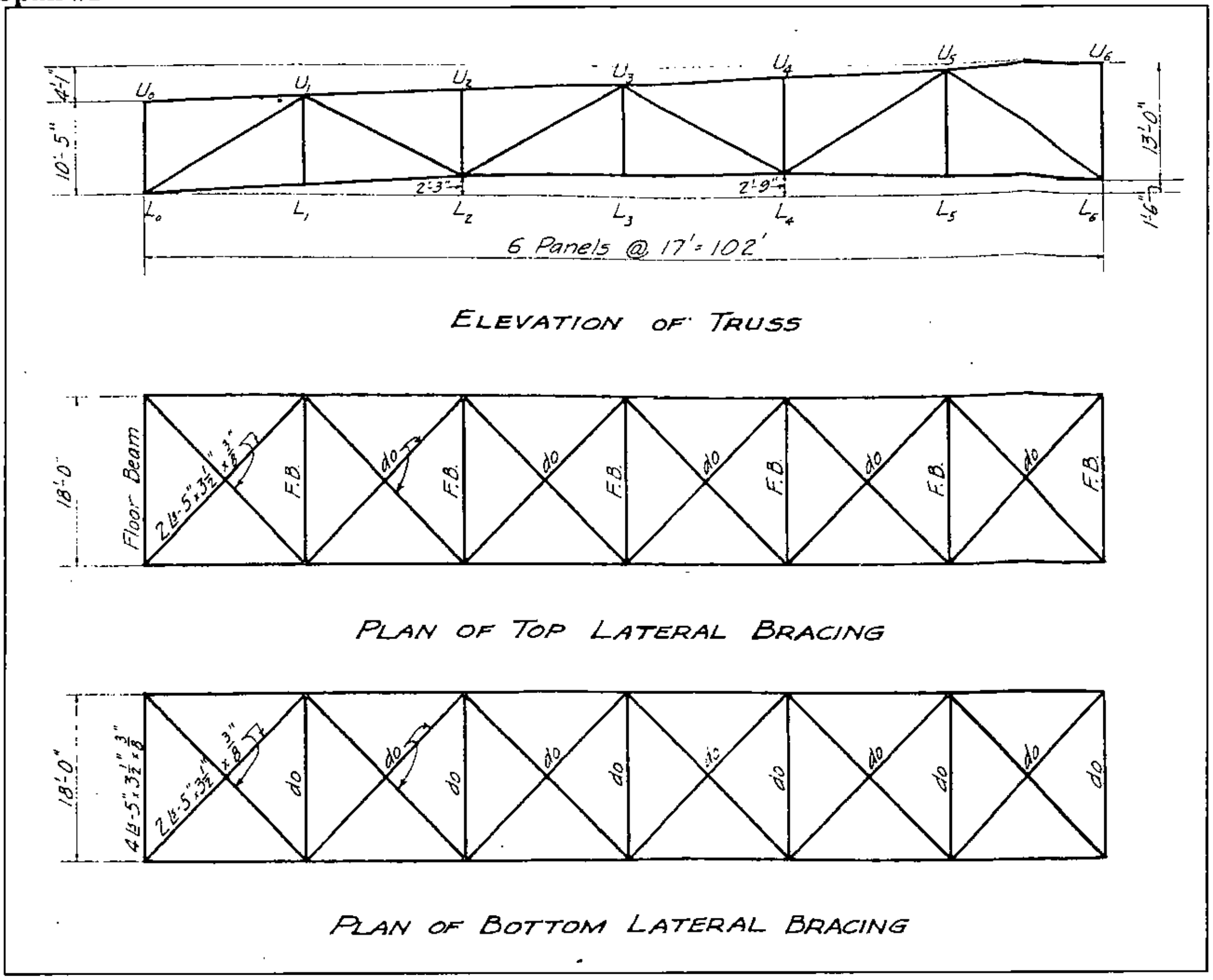
Span #	Length	Description
Span #0	26'	Reinforced concrete structure, walls and slab on footings
Span # 1	102'	Simple span Warren Truss variable depth, fixed left, roller right
Span #2	125'	Continuous with #3 span Warren Truss variable depth, fixed left, rocker right
Span #3	163'	Continuous with #2 span Warren Truss variable depth, rocker left, roller right
Span #4	200'	First span in sequence of three continuous trusses on Warren Pattern Deck Truss, roller left, rocker right
Span #5	275'	Second span in sequence of three continuous trusses on Warren Pattern. Through truss, rocker left, fixed right
Span #6	200'	Third span in sequence of three continuous trusses on Warren Pattern, Deck Truss, fixed left , roller right
Span #7	163'	Simple span Warren Truss variable depth, fixed right, roller left
Span #8	163'	Continuous with #9 Warren Truss variable depth, rocker right, roller left
Span #9	125'	Continuous with #8 Warren Truss variable depth, fixed right, rocker left
Span #10	26'	Reinforced concrete structure, walls and slab on footings

The superstructure is supported on two abutments and eight (8) piers. The trusses on spans 1, 2, 3 and 7, 8, 9 are spaced 18' apart and spans 4, 5, 6 are spaced 32' apart.

The roadway consists of two 12' lanes and 3'-7" sidewalks on each side. The roadway from the Dover Point abutment at elevation 132.43 ramps up on a 4 percent slope for 483.5' followed by a 500' vertical curve with a high point at the middle of span 5 and thence down on a 4 percent slope for 544.5' to the Newington abutment at elevation 129.99. Due to the different elevations at the end of the bridge and the different distances from the center of the main span to the abutments the bridge spans are not symmetrical. Spans 1, 2, 3, 4 and 6, 7, 8, 9 are deck trusses with the middle span #5 a through truss. The asymmetry is further evident in the fact that spans 8 and 9 have a much lower clearance from the surface of the water that the rest of the spans

<u>Superstructure</u>

Span #1



Span #1 profile and top and bottom chord bracing plans (NHDOT)

The top chord slopes up on a 4 percent grade while the lower chord is on a slight curve with offsets from the horizontal of 2'–3" at panel point L2, 2'–9" at panel point L4 and 1'–6" at panel point L6. Panel lengths are 17' with the depth of truss varying from panel point to panel point with the depth at panel point 0 being 10'–5" and at panel point 6 being 14'–0". The top chord bracing consists of crossing pairs of 5" x 3½" x 3/8" angle irons between the floor beams. The lower chord bracing consists of the same crossing pairs of 5" x 3½" x 3/8" angle irons between an assembly of four back-to-back 5" x 3½" x 3/8" angle irons. The truss member sizes are as follows:

MEMBER	SECTION	ASSEMBLY
U_0-U_1	Cover PL 18"×3/8" 2-[-12"@ 25#	][(10½)
U_1-U_3	Cover PL 18"×3/8" 2-[-12"@35# 2PL 11½"×1/2"	][
U_3-U_5	Cover PL 18"×3/8" 2-[-12"@35# 2PL 11½"×3/8"	
U_5-U_6	Cover PL 18"×3/8" 2-[-12"@ 25#	][
L_0-L_2	2-[-12"@ 40#	] [
L_2-L_4	2-[-12"@ 40# 2 PL-11½"×3/4"	]I I[
L_4-L_6	2-[-12"@ 35#	] [
U_1-L_0	2-[-12"@ 35# 2 PL-11½"×1/2"	]I I[
U_1-L_2	2-[-12"@ 35#	] [
U_3-L_2	2-[-12"@ 25#	
U_3-L_4	2-[-12"@ 25#	
U_5-L_4	2-[-12"@ 35#	
U_5-L_6	2-[-12"@ 30# 2 PL-11½"×1/2"	]I I[
U_0-L_0	2-[-12"@ 25#	] [
U_2-L_2	2-[-12"@ 25#	
	2-[-12"@ 25# U_1-L_1, U_3-L_3, U_4-L_4, U_5-L_5, U_6-L_6	

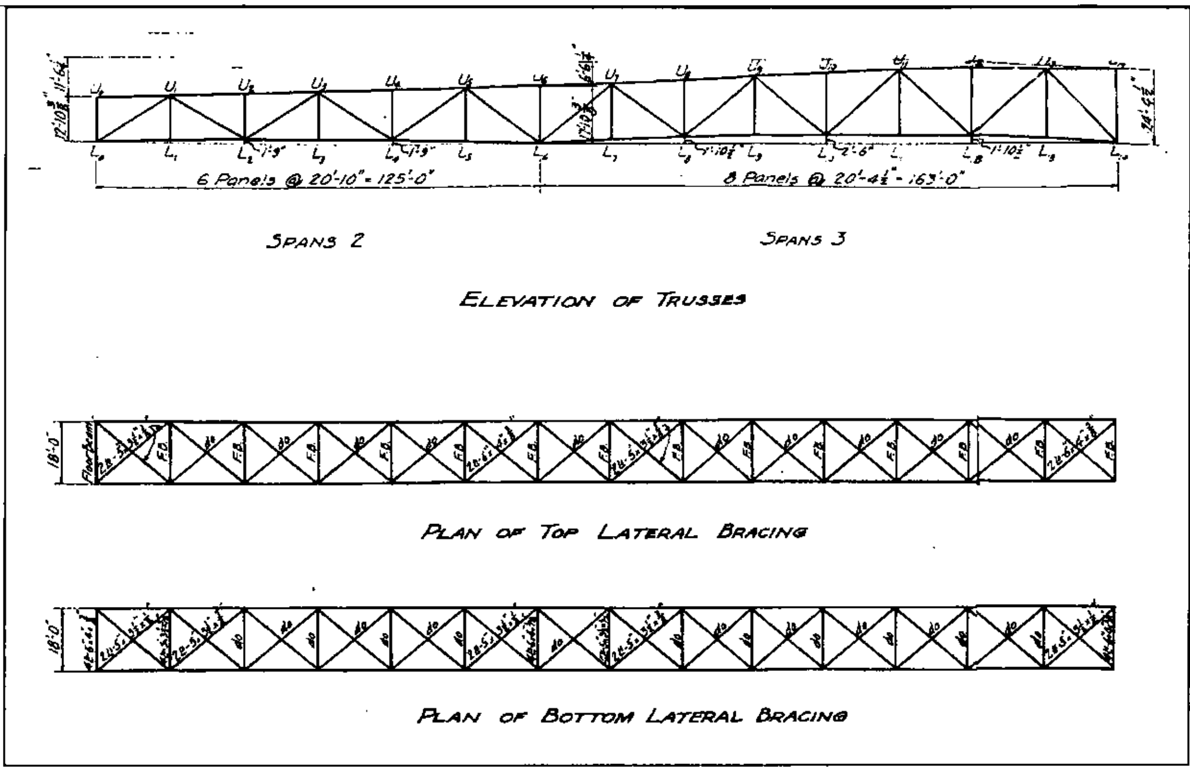
Table of truss member sizes lattice bars not shown (NHDOT)

Members are built up with 12" deep channel sections weighing 25 or 35 pounds/foot and 11½" – ½' or 3/8" thick plates riveted together and onto 5/8" thick gusset plates at each joint. with 7/8" diameter rivets. Double lattice members connect the channel legs.

The cross, sway, bracing between the trusses in the transverse direction consists of the floor beam and an assembly of four back-to-back 5" x 3½" x 3/8" angle irons connecting the lower chord panel points at L0, L2, L4, and L6 with crossing pairs of 5" x 3½" x 3/8" angle irons.

Span #2 & #3

The top chord slopes up on the 4 percent grade from U0 to U14 while the lower chords are on a slight curve with offsets from the horizontal of 0" at panel point L0, 1'–9" at panel point L2, 1'– 9" at panel point L4 and 0 at panel point L6, 1'–10½" at panel point L8, 2'–6" at panel point



Spans #2 & #3 profile and top and bottom chord bracing plans (NHDOT)

Note:
Spans #8 & #9 are mirror images of spans #2 & #3

L10 , 1'–10½" at panel point L10, and 0" at panel point L12. Panel lengths are 20'–10" for span #2 and 20'–4½" for span #3. The offsets from the horizontal of 0" at panel point L0, 1'–9" at panel point L2, 1'–9" at panel point L4 and 0" at panel point L6, 1'–10½" at panel point L8, 2'–6" at panel point L10 , 1'–10½" at panel point L12, and at L14, 0". The depth of truss varies from panel point to panel point, with the depth at panel point 0 being 12'–10$^{3}/_{8}$" and at panel point L6 being 17'–$^{3}/_{8}$" and at panel point L14 being 24' 4 1/2". The top chord bracing consists of crossing pairs of 5" x 3½" x $^{3}/_{8}$" angle irons between the floor beams. The lower chord bracing consists of the same crossing pairs of 5" x 3½" x $^{3}/_{8}$" angle irons between an assembly of four back to back 6" x 4" x $^{3}/_{8}$" angle irons.

The members are built up with 12" deep channel sections weighing 25 or 35 #/foot and 11½" – ½" or $^{3}/_{8}$" thick plates riveted together and onto $^{5}/_{8}$" thick gusset plates at each joint. with $^{7}/_{8}$" diameter rivets. Double lattice members connect the channel legs.

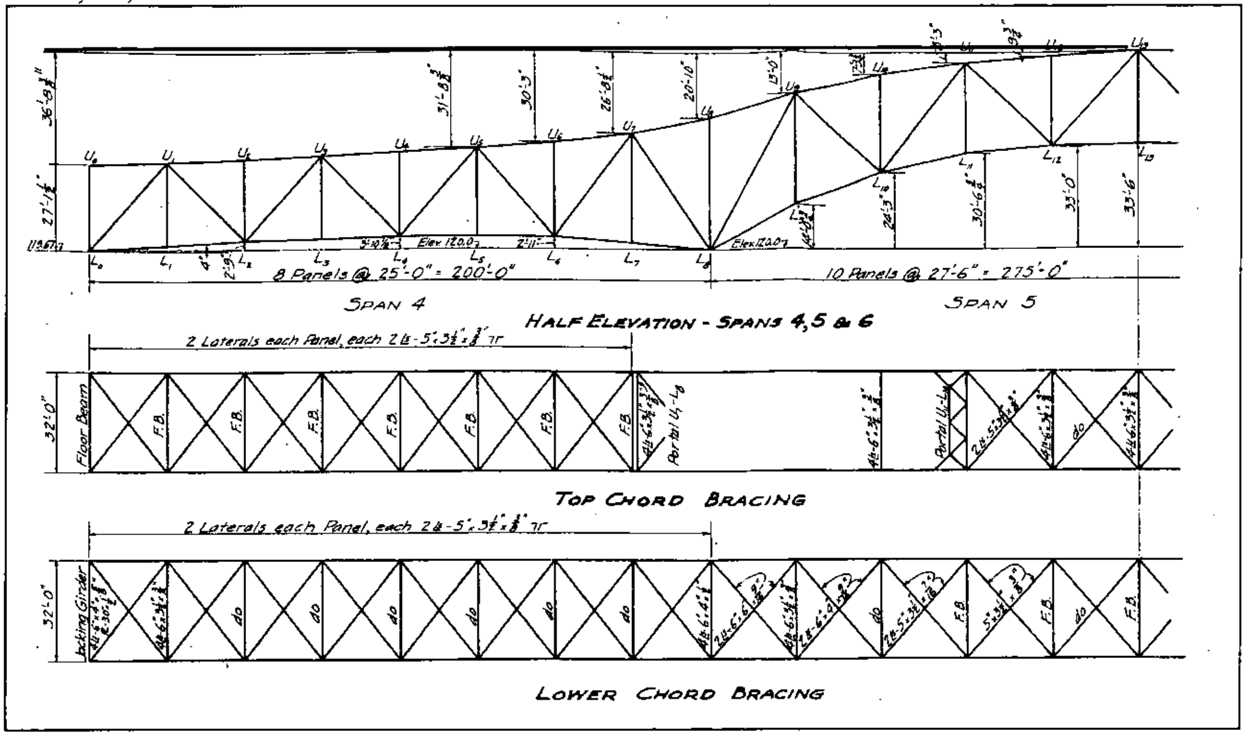
The truss member sizes are as follows:

MEMBER	SECTION		ASSEMBLY
U_0-U_1	Cover Pl. 18" x 3/8"	2-12" [@ 25#	
U_1-U_3	Cover Pl. 18" x 3/8"	2-12" [@ 25# 2 Pl 11½" x 3/8"	][
U_3-U_5	Cover Pl. 18" x 3/8"	2-12" [@ 25#	
U_5-U_7	Cover Pl. 18" x 3/8"	2-12" [@ 40# 2 Pl. 11½" x ½"	
U_7-U_9	Cover Pl. 18" x 3/8"	2-12" [@ 25#	
U_9-U_{11}	Cover Pl. 18" x 3/8"	2-12" [@ 40# 2 Pl 11½" x 3/8"	] [
U_{11}-U_{13}	Cover Pl. 18" x 3/8"	2-12" [@ 25# 2 Pl 11½" x 3/8"	
U_{13}-U_{14}	Cover Pl. 18" x 3/8"	2-12" [@ 25#	
L_0-L_2	2-12" [@ 35#		
L_2-L_4	2-12" [@ 35#		
L_4-L_6	2-12" [@ 30#	2 Pls 11½" x 3/8"	
L_6-L_8	2-12" [@ 35#		] [
L_8-L_{10}	2-12" [@ 35#	2 Pls 11½" x 3/8"	
L_{10}-L_{12}	2-12" [@ 40#	2 Pls 11½" x ½"	
L_{12}-L_{14}	2-12" [@ 25#		
U_1-L_0	2-12" [@ 40#		
U_1-L_2	2-12" [@ 25#		
U_3-L_2	2-12" [@ 25#		] [
U_3-L_4	2-12" [@ 35#		
U_5-L_4	2-12" [@ 40#		
U_5-L_6	2-12" [@ 40#	2 Pls 11½" x 5/8"	
U_7-L_6	2-15" [@ 45#	2 Pls 14½" x ½"	][
U_7-L_8	2-12" [@ 35#	2 Pl 11½" x 3/8"	
U_9-L_8	2-12" [@ 30#		
U_9-L_{10}	2-12" [@ 25#		
U_{11}-L_{10}	2-12" [@ 25#		] [
U_{11}-L_{12}	2-12" [@ 25#		
U_{13}-L_{12}	2-12" [@ 30#		
U_{13}-L_{14}	2-12" [@ 40#	2 Pl 11½" x 3/8"	
U_0-L_0	2-12" [@ 25#		
U_1-L_1	U_3-L_3, U_5-L_5, U_7-L_7, U_9-L_9, U_{11}-L_{11}, U_{13}-L_{13}	2-12" [@ 25#	
U_2-L_2	U_4-L_4	2-12" [@ 25#	
U_6-L_6		2-12" [@ 25#	] [
U_{10}-L_{10}	U_8-L_8, U_{12}-L_{12}	2-12" [@ 25#	
U_{14}-L_{14}		2-12" [@ 25#	

Member sizes Spans #2, # 3, #8, #9 lattice bars not shown (NHDOT)

The cross, sway, bracing between the trusses in the transverse direction consists of the floor beam and an assembly of four back to back 6" x 4" x 3/8" connecting the lower chord panel points at L0, L6, L14 with crossing pairs of 6" x 4" x 3/8" at L0, 6" x 4" x ½" at L6 and 6" x 4" x 5/8" at L14. At panel points L2, L4, L8, L10, L12 the bracing consists of the floor beam and an assembly of four back to back 5" x 3½" x $^3/_8$" angle irons connecting the lower chord panel points with crossing pairs of 5" x 3½" x $^3/_8$" angle irons.

Spans # 4, #5, #6 Continuous Trusses



Spans #4, #5, #6 profile and top and bottom chord bracing plans

Half truss shown, right side mirror image (NHDOT)

The top chord slopes up on the 4 percent grade from U0 to U5. It continues in a reverse curve with offsets from the peak point at U13 as follows:

Upper panel point location	Offset from Horizontal at panel point U13
U13	0"
U12	9 ¾"
U11	3'–3"
U10	7'–3¾"
U9	13'–0"
U8	20'–10"
U7	26'–8½2"
U6	30'–3"
U5	31'–8$^3/_8$"

The lower chord from L0 to L8 is similar to the previous trusses but the lower chord from L8 to L13 has much larger offsets from the horizontal. The lower chord offsets are as follows:

Lower panel point location	Offset from horizontal at panel point L0 & L8
U13	33'–6"
U12	33'–0"
U11	30'–6¾"
U10	24'–3"
U9	14'–¾"
U8	0"
U6	2'–11"
U4	3'–10 1/8"
U2	2'–9"
U0	0"

The depth of truss varies from panel point to panel point with the depth at panel point 0 being 27'–1½", at panel point L8, 42'–11 7/8" and at the peak, L13, 30'–3 7/8". The top chord bracing consists of crossing pairs of 5" x 3½" x 3/8" angle irons between the floor beams. The lower chord bracing consists of the same crossing pairs of 5" x 3½" x 3/8" angle irons between an assembly of four back to back 6" x 4" x 3/8" angle irons.

The members are built up with 12", 15" and 18" deep channel sections weighing between 25 or 58 pounds/foot and 16" - 20" plates with thicknesses varying from 3/8" to 9/16" riveted together and onto gusset plates with thicknesses from ¾" to 7/8" thicknesses at each joint. with 7/8" diameter rivets. Double lattice members connect the channel legs.

The cross, sway, bracing between the trusses in the transverse direction consists is more complex in these spans as from L0 to L10 the sway braces are below the deck, as on the approach spans, and some, L12 and L13, above the deck with panel point 11 having bracing both above and below the deck. The size of the sway brace members is shown in tabular form below:

Panel Point	Cross bracing paired	Transverse member lower	Transverse member upper	Added jacking plates
0	5" x 3½" x 3/8"	4'–6" x 4" x 5/8"	Floor beam	30' x ½"
2	5" x 3½" x 3/8"	4'–6" x 3½" x 3/8"	Floor beam	-
4	5" x 3½" x 3/8"	4'–6" x 3½" x 3/8"	Floor beam	-
6	5" x 3½" x 3/8"	4'–6" x 3½" x 3/8"	Floor beam	-
8	5" x 3½" x 3/8"	4'–6" x 3½" x ½"	Floor beam	-
9	5" x 3½" x 3/8" single angle	4'–6" x 3½" x 3/8"	Floor beam	-
10	6" x 4" x 3/8" on V (down) pattern	4'–6" x 3½" x 3/8"	Floor beam	-

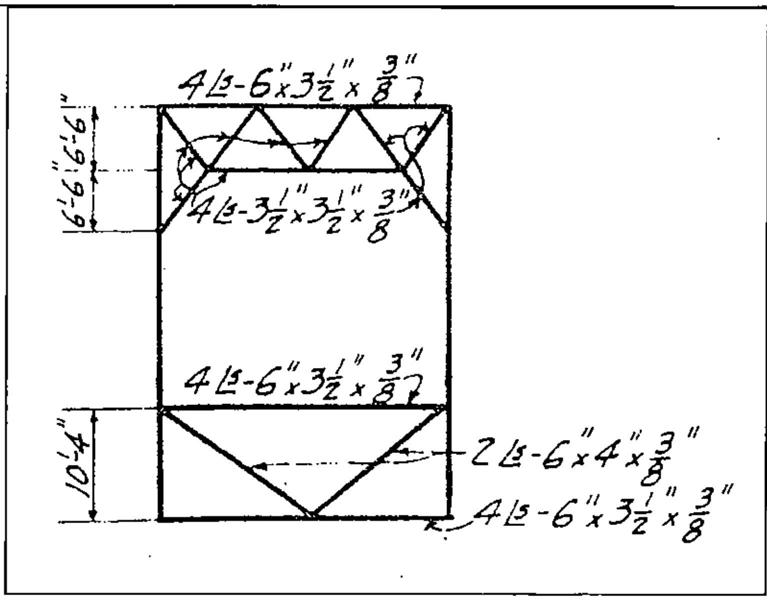
12	6" x 4" x $^3/_8$" on V (up) pattern	Floor beam	4'–6" x 3½" x $^3/_8$" 4'–6" x 3½" x $^3/_8$"	-
13	4'–6" x 4" x $^3/_8$" on V(up) pattern	Floor beam	4'–6" x 3½" x $^3/_8$" 4'–6" x 3½" x $^3/_8$"	-

The truss member sizes are shown on the following page.

MEMBER	SECTION		ASSEMBLY
U_0-U_1	Cover Pl. 18"×3/8"	2-12" [@ 25#	
U_1-U_3	Cover Pl. 18"×3/8"	2-12" [@ 25# 2 Pl. 11½"×3/8"	
U_3-U_5	Cover Pl. 18"×3/8"	2-12" [@ 25#	
U_5-U_7	Cover Pl. 18"×3/8"	2-12" [@ 40# 2 Pl. 11½"×½"	
U_7-U_9	Cover Pl. 18"×3/8"	2-12" [@ 25#	
U_9-U_{11}	Cover Pl. 18"×3/8"	2-12" [@ 40# 2 Pl. 11½"×3/8"	
U_{11}-U_{13}	Cover Pl. 18"×3/8"	2-12" [@ 25# 2 Pl. 11½"×3/8"	
U_{13}-U_{14}	Cover Pl. 18"×3/8"	2-12" [@ 25#	
L_0-L_2	2-12" [@ 35#		
L_2-L_4	2-12" [@ 35#		
L_4-L_6	2-12" [@ 30#	2 Pls. 11½"×3/8"	
L_6-L_8	2-12" [@ 35#		
L_8-L_{10}	2-12" [@ 35#	2 Pls. 11½"×3/8"	
L_{10}-L_{12}	2-12" [@ 40#	2 Pl. 11½"×½"	
L_{12}-L_{14}	2-12" [@ 25#		
U_1-L_0	2-12" [@ 40#		
U_1-L_2	2-12" [@ 25#		
U_3-L_2	2-12" [@ 25#		
U_3-L_4	2-12" [@ 35#		
U_5-L_4	2-12" [@ 40#		
U_5-L_6	2-12" [@ 40#	2 Pls. 11½"×5/8"	
U_7-L_6	2-15" [@ 45#	2 Pls. 14½"×½"	
U_7-L_8	2-12" [@ 35#	2 Pl. 11½"×3/8"	
U_9-L_8	2-12" [@ 30#		
U_9-L_{10}	2-12" [@ 25#		
U_{11}-L_{10}	2-12" [@ 25#		
U_{11}-L_{12}	2-12" [@ 25#		
U_{13}-L_{12}	2-12" [@ 30#		
U_{13}-L_{14}	2-12" [@ 40#	2 Pl. 11½"×3/8"	
U_0-L_0	2-12" [@ 25#		
U_1-L_1	U_3-L_3, U_5-L_5, U_7-L_7, U_9-L_9, U_{11}-L_{11}, U_{13}-L_{13}	2-12" [@ 25#	
U_2-L_2	U_4-L_4	2-12" [@ 25#	
U_6-L_6		2-12" [@ 25#	
U_{10}-L_{10}	U_8-L_8, U_{12}-L_{12}	2-12" [@ 25#	
U_{14}-L_{14}		2-12" [@ 25#	

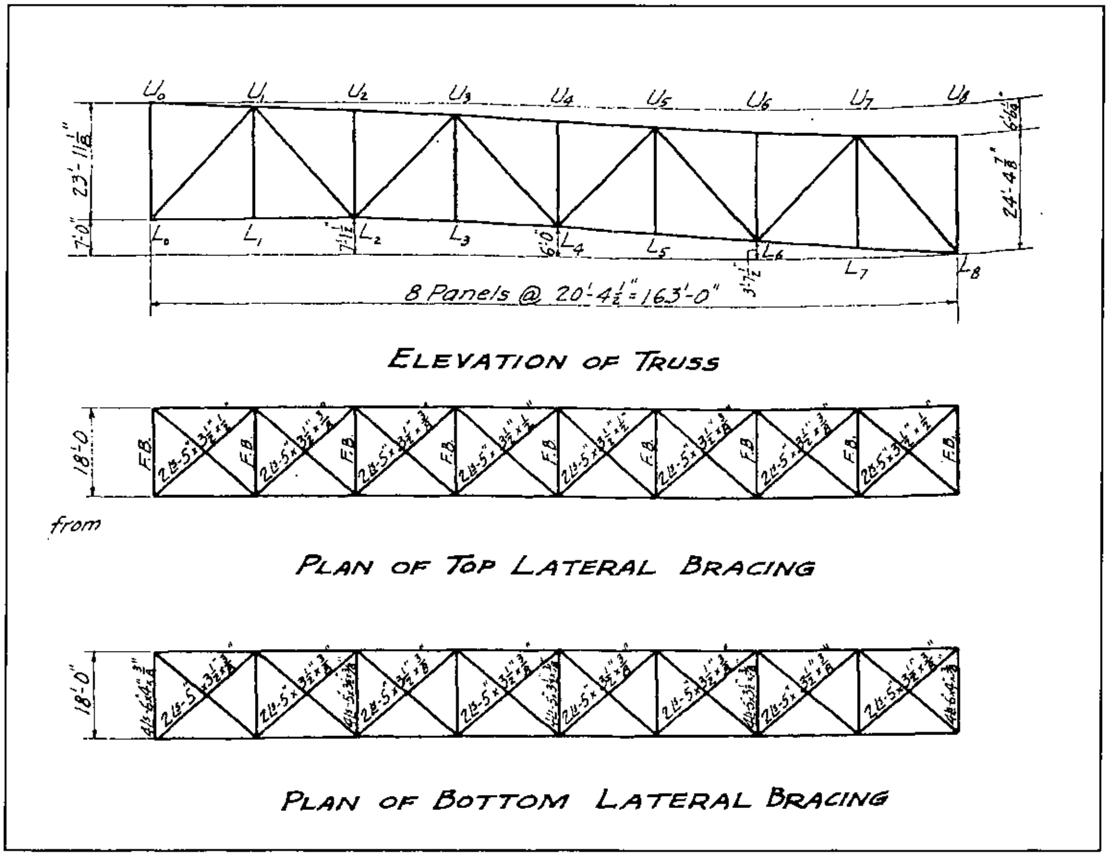
* ... trusses may cause the structure to act as a contin...

Member sizes Spans #4, #5 #6 lattice bars not shown (NHDOT)



Sway Bracing panel point #1 (NHDOT)

Span #7



Span # 7 (NHDOT)

The top chord slopes up on the 4 percent grade while the lower chord is on a greater curve than span #1, in order to accommodate the 7'–0" difference in top of pier elevations, with offsets from the horizontal of 7'–0" at panel point L0, 7'–1½" at panel point L2, 6'–0" at panel point L4 and 3'–7½" at panel point L6 and 0 at panel point L8. Panel lengths are 20'-4½" with the depth of truss varying from panel point to panel point with the depth at panel point 0 being 23'–11⅛" and at panel point 8 being 24'– 4⁷/₈". The top chord bracing consists of crossing pairs of 5" x 3½" x ³/₈" angle irons between the floor beams. The lower chord bracing consists of the same crossing pairs of 5" x 3½" x ³/₈" angle irons between an assembly of four back to back 5" x 3½" x ³/₈" angle irons. The truss member sizes are as follows:

MEMBER	SECTION	AREA GROSS	AREA NET	ASSEMBLY
U0-U1	2-⊏-15" @ 33.9# Cover PL. 18" x 3/8"	26.6		][
U1-U3	2-⊏-15" @ 50# Cover PL. 18" x 3/8"	36.0		
U3-U5	2-⊏-15" @ 45# 2 PL. 14½" x ½" Cover PL. 18" x 3/8"	47.6		]][[
U5-U7	2-⊏-15" @ 50# Cover PL. 18" x 3/8"	36.0		]][[
U7-U8	2-⊏-15" @ 33.9# Cover PL. 18" x 3/8"	26.6		
L0-L2	2-⊏-15" @ 35#	20.4	17.5	] [
L2-L4	2-⊏-15" @ 50# 2 PL. 14½" x ½"	43.8	37.2	]][[
L4-L6	2-⊏-15" @ 50# 2 PL. 14½" x ½"	43.8	37.2	
L6-L8	2-⊏-15" @ 35#	20.4	17.5	] [
U1-L0	2-⊏-15" @ 40# 2 PL. 14½" x 3/8"	34.3		]][[
U1-L2	2-⊏-15" @ 40#	23.4	20.1	
U3-L2	2-⊏-15" @ 33.9#	19.8	16.9	
U3-L4	2-⊏-15" @ 55#	32.2		
U5-L4	2-⊏-15" @ 55#	32.2		
U5-L6	2-⊏-15" @ 33.9#	19.8	16.9	] [
U7-L6	2-⊏-15" @ 40#	23.4	20.1	
U7-L8	2-⊏-15" @ 40# 2 PL. 14½" x 3/8"	34.3		
U8-L8	2-⊏-12" @ 25#	14.6		
U2-L2	2-⊏-12" @ 25# U1-L1, U3-L3, U5-L5, U6-L6, U7-L7, U8-L8	14.6		
U4-L4	2-⊏-12" @ 30#	17.6		

Span #7 member sizes, latticework not shown (NHDOT)

Deck Structure

The floor beams on span #1 are W 18" x 86# beams resting on the top chord of the truss. Five stringer beams span between panel points U0 and U6 with two outer beams being W 18" x 47 and the three interior beams being W 20" x 60s.

The floor beams on span #2, #3, #8, #9 are W 20" x 80# beams resting on the top chord of the truss. Five stringer beams span between panel points U0 and U14 with two outer beams being W 20" x 55 and three interior beams being W 21" x 67s.

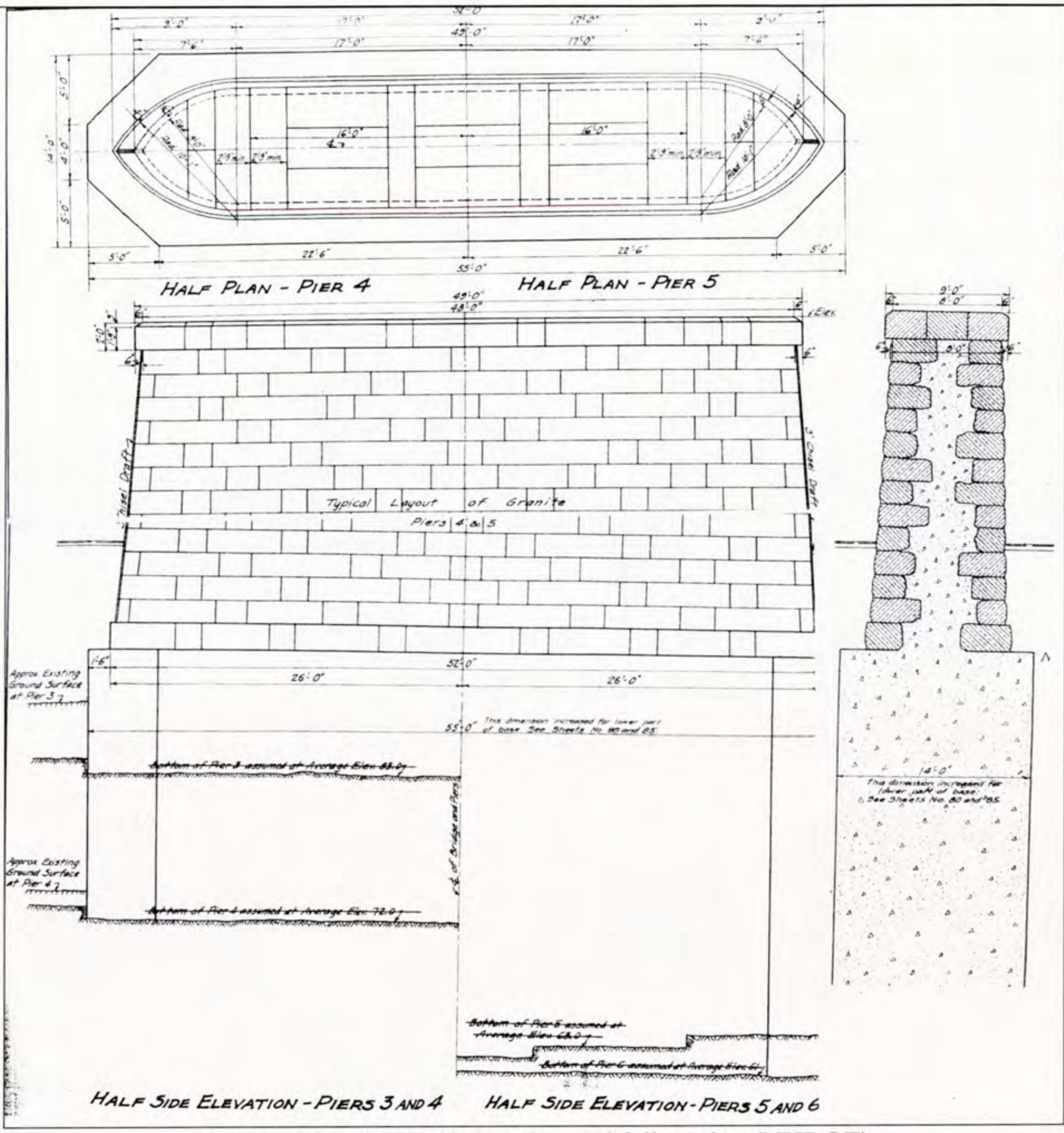
The floor beams on span #4, #5, #6 are built up riveted beams consisting of a web plate 40" x ¾", 4 angles 6" x 6" x ⁵/₈", with two cover plates (one top and one bottom) 13" x ½" - 20' long centered on the axis of the bridge. Web stiffener angles 4" x 3" x ³/₈" on both sides of the web are spaced 3'–1½" on center. The beams are connected to the vertical members of the truss by riveting and gusset plates and angles.

Five stringer beams span between panel points U0 and U13 and U0 (symmetrical layout) with the two outer beams being W 21" x 73# and the three interior beams being W 24" x 85#. The stringers are riveted to webs of the main floor beams and sit on seat angles also riveted to webs of the beams.

The surface of the deck is reinforced concrete 8½" thick (7" structural concrete and 1½" concrete wearing surface). The deck is reinforced with transverse rebar 6" on center spanning the stringers on the top and bottom surfaces of the deck. These rebar are connected with reinforcing trusses 5½" out to out vertically, with trussing between the top and bottom bars having a minimum weight of ½ pound per lineal foot of deck width. Longitudinal deck reinforcing (temperature steel) consisted of $^5/_8$" reinforcing bars 6" on center. Concrete sidewalks integral with the curbing rests on the outer stringers and channels or wide flange beams.

Railing posts at the panel points are twin 8" channels weighing 22.8 pounds/foot. Intermediate posts are twin 6" channels weighting 15.3 pound/foot. A pair of 3" diameter extra-heavy pipe span the posts with vertical $^7/_8$" spokes 5" on center.

Foundations and Abutments
The maximum depth of water at flood tide is 38' under spans #6 and #7. The riverbed is primarily bedrock of slaty material covered by "4 feet to 10 feet of clay, sand and gravel varying from a fairly compact mixture at the top to hardpan near the ledge surface" (*Engineering News Record* 1934A:388).



Pier #6 Half plan, half elevation and full section (NHDOT)

Pier dimensions vary due to the depth of bedrock and the spacing of the trusses. Concrete footings were poured from bedrock to elevation 92 with tapered stone faced and concrete backed piers extending to various elevations as shown in the table below. The piers are pointed on both ends in the form of a gothic arch similar to ice breakers. Pier #6 in plan and elevation is shown above to illustrate the construction of a typical pier.

Pier	Concrete	Base	Stone faced	Pier	Top elevation
#	Plan dimensions	Top Elev.	Plan Dim. base	Height	-
1	13.5' x 39.8'	92.0'	9' 2" x 36' 4"	25'	117.0'
2	15' x 40'	92.0'	9' 5" x 36' 4"	25'	117.0'

3	17.4' x 58'	92.0'	10'–5" x 52'	25'	117.0'
4	16.1' x 57.8'	92.0'	10'–5" x 52'	25'	117.0'
5	17.9' x 59.1'	92.0'	10'–5" x 52'	25'	117.0'
6	15.6' x 58.2'	92.0'	10'–5" x 52'	25'	117.0'
7	15' x 41.2'	92.0'	8'–10" x 35'–3"	18'	110.0'
8	14.8' x 40.1'	92.0'	8'–10" x 35'–3"	18'	110.0'

Piers #7 and # 8 were lower to accommodate the additional length of 4 percent grade and the fact that the Newington abutment was 2.44' lower than the Dover abutment. The drawings indicate that the base elevation of concrete piers # 4, 5, 6, 7 was modified during construction to match actual bottom conditions and the need to place the concrete by tremie methods.

The bridge's abutments are unadorned steel-reinforced concrete structures measuring 28' (water elevation) by 33' (side elevations). The height of the abutments is approximately 17' on the highest (water) side. The abutments rest on four 5'-square (land side) and one 7' x 30' (water side) footings. Three-foot wide sidewalks are cantilevered up and out from the sides of the abutments. A railing, original to the bridge, is located to the outside of both sidewalks on both abutments. It consists of three lengths of 8'–3" steel pipe railing alternating with large (2' x 1'–2") concrete fence posts.

Alterations/Maintenance 1946 to 2003

1946 The first significant repairs to the bridge were made in 1946 when the concrete roadway slabs were repaired with a sprayed-on gunite layer. Evidently, this was to remedy a problems with some of the concrete which was chipping or spalling resulting in a rough riding surface with some possible reinforcing bar exposure and rusting.

1950 First major repainting.

1962 Sidewalk concrete holes were repaired and the engineers indicated that development of the holes was an indication of more to come. Sometime in the early 1960s an asphaltic concrete overlay was placed over the entire deck of the bridge.

1966 New Span begun adjacent to the General Sullivan.

1968 Concrete slab at approach to bridge settled and was dug up and replaced. (Not a part of the bridge superstructure.)

1970 A major inspection of the bridge was undertaken in the summer of 1970 including an underwater inspection of the pier foundations and stone work. A significant amount of rust bulge was found causing separation of steel plates and channels in the lower chord members. The deck concrete was cracked in many places, and rust stains from the reinforcing bar were evident. Eighteen expansion shoes and ten fixed shoes were inspected, cleaned and repaired. Granite stone facing and capstones were repointed as necessary. Underwater repair to the concrete pier footings was performed on pier #4 and pier #6.

1971 Ongoing repair to pier concrete and pointing of stonework was done.

1973 Two deck expansion joints were repaired, but shortly after, the surface cracked resulting in a 2" lip.

1978 Comprehensive inspection of deck concrete undertaken. The conclusion was that the sidewalks and edges of the deck needed full depth repair/replacement.

1979- 1980 Bridge maintenance crew replaced the concrete sidewalks in sections.

1978 Repairs to piers and pointing of granite stone facing of piers were done.

1980 Another new span was proposed to match the 1966 span. When the new bridge was proposed the engineers stated "The General Sullivan bridge is in tough shape, but it is structurally sound...It will not fall into the bay."

1983 Placed shoring under deck. Evidently a serious deck problem had developed. The record is not clear as to the extent of the shoring.

1984 New span completed and General Sullivan Bridge closed to vehicular traffic. Bicycles and pedestrians permitted on the bridge.

1989 Replaced concrete sidewalk and deck sections. An inspection report dated June 1989 noted "the steel superstructure is generally sound ... stringers are severely rusted, with some area rusted throughout. The floor beams are more severely rusted and have section losses." The bridge was limited to fifteen ton loading.

1999 – 2002 In this period sidewalks and deck concrete were replaced as necessary for the use of pedestrians and cyclists.

Note: Throughout its life on a scheduled basis the expansion bearings were greased and general stone repointing was undertaken. Minor electrical and lighting work was also performed. There is no record of any major repair on the steel work of the bridge even though rusting was reported early in its life.

Comparative Analysis

It is clear that there are no comparable bridges to the General Sullivan in New Hampshire. Although short-span continuous steel plate girder bridges were being designed by the New Hampshire Highway Department by the early 1930s[22], there do not appear to have been other long-span continuous truss bridges in New Hampshire of the same era. At 1,585', the General Sullivan is the longest extant pre-1940 bridge in the state. It is also the longest pre-1971 truss bridge.[23] It is, overall, the fifth longest bridge in New Hampshire today.[24] Of the bridges that are longer, many have not reached the fifty-year National Register statutory period. Longer bridges include only the

[22] See Story 2002:9. Also, two longer (continuous girder) bridges across the Connecticut River, the bridge between Littleton, New Hampshire and Waterford, Vermont and the Ledyard Bridge (between Hanover New Hampshire and Norwich, Vermont), date from 1934/35.

[23] The next longest truss bridge in the state is the Queen City Bridge in Manchester built in 1923, which is 1190' long.

[24] The bridge is the fourth longest if the two spans of the new bridge over Little Bay are considered as one bridge.

Sarah M. Long/US. Route 1 Bypass Bridge (1940), the Piscataqua River (I-95) Bridge (1971) and the bridges built over Little Bay to replace the General Sullivan Bridge [the Capt. John F. Rowe (1984) and Eastern Turnpike Bridge (1966)]. It is possible that it was the longest bridge ever built in New Hampshire when it was constructed. Comparable in terms of length, the Neil R. Underwood Bridge over the Hampton River, once a wood bridge, was originally a mile long. Aside from its length, the bridge was a major engineering effort, which was matched only by Memorial Bridge in terms of effort and difficulty in construction.

Comparable bridges to the General Sullivan on a national level include only the trio of other early Faye, Spofford, continuous truss bridges, including the 1929 Lake Champlain Bridge, the 1934 Bourne Bridge and the 1935 Sagamore Bridge. Each of these bridges significantly influenced future continuous truss highway bridge design and each made incremental improvements to the technology, aesthetics and construction methods used in the design of continuous truss highway bridges.

44. National or State Register Criteria Statement of Significance:

In 1988, representatives from the New Hampshire Department of Transportation, the state Historic Preservation Office and the Federal Highway Administration reviewed the General Sullivan Bridge, as part of the thematic review of continuous steel truss bridges in the state. After judging the bridge's historicity, technological significance and environmental quality, the committee deemed the bridge eligible for National Register of Historic Places consideration. The bridge is eligible under the following Criteria:

Criterion A: The General Sullivan Bridge is eligible for the National Register under Criterion A. It is significant in the area of transportation at a state level of significance. The construction of the bridge, along with associated bridge and road projects, forever changed transportation routes in this area of the state. The bridge established (or re-established) patterns of transportation between Portsmouth (and, more generally, the eastern seaboard) and the northern portion of the state including the Lakes Region. It also re-established, in coordination with the construction of the Scammell Bridge, a through route between Concord and Portsmouth. The bridge project was also one of the first in the state to use a self-liquidating financing system.

Criterion B: There are no known significant persons associated with the General Sullivan Bridge that would make the structure eligible under Criterion B.

Criterion C: The General Sullivan Bridge is eligible for the National Register under Criterion C at a national level of significance in the area of engineering. The General Sullivan Bridge is an important U.S. example of an early continuous truss highway bridge and its design and construction contributed significantly to the advancement of twentieth century American bridge technology. The bridge is one of four major bridges of the same type, style and time period designed by the firm of Fay, Spofford and Thorndike, that as a group significantly influenced future continuous truss highway bridge design in the areas of technology, aesthetics and construction methods.

In particular, the General Sullivan represents an important step in the evolution of the continuous truss highway bridge because it: 1) incorporated special features of the earlier Lake Champlain prototype that were proved economically sound; 2) demonstrated the practical application of a new technology for weighing bridge reactions; and 3) established, or helped establish, a markedly reduced economical span length for the continuous truss. The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T was copied for years to come for major and minor highway bridges around the country where aesthetics and cantilever construction were necessary factors. As new bridge technologies and design concepts developed they were integrated into the design type to create hybrid forms of continuous arched truss bridges.

Fay, Spofford and Thorndike, the engineering firm for the bridge, was one of the era's few bridge engineering firms of national repute. During this era the firm pioneered the field of continuous truss bridges; partner Charles Spofford was the author of the seminal 1937 textbook *The Theory of Continuous Structures and Arches.* The firm enjoyed a long and distinguished history in bridge design and remains in business today.

The bridge is also significant because of the extreme circumstances involved in its construction. These conditions included exceptional tides and currents as well as weather conditions that caused large, ice flows that endangered the structure as it was being constructed.

45. Period of Significance:

1934-1964

46. Statement of Integrity:

Although not currently in use, the General Sullivan Bridge retains a high degree of physical integrity. The bridge retains integrity of location, design, setting, materials, workmanship, feeling and association. Physical changes to the bridge as discussed in earlier sections of this form have been minor, and none affect character-defining features. The bridge's original setting has been altered minimally by the construction of the nearby Dover Point Bridges (1966, 1984). For integrity issues related to Hilton Park see DOV0150.

47. Boundary Discussion: Please see page 81 for corrected boundary.

The area covered in this nomination includes the footprint of the bridge itself, its abutments, approach roads and the west section of Hilton Park, which was acquired to provide an appropriate setting for the bridge. The boundaries for the west section of Hilton Park are defined as the banks of Little Bay on the south and west sides, the west (Little Bay) side of the approach road to the General Sullivan Bridge on the east, and the legal boundary of the state-owned property on the north side.

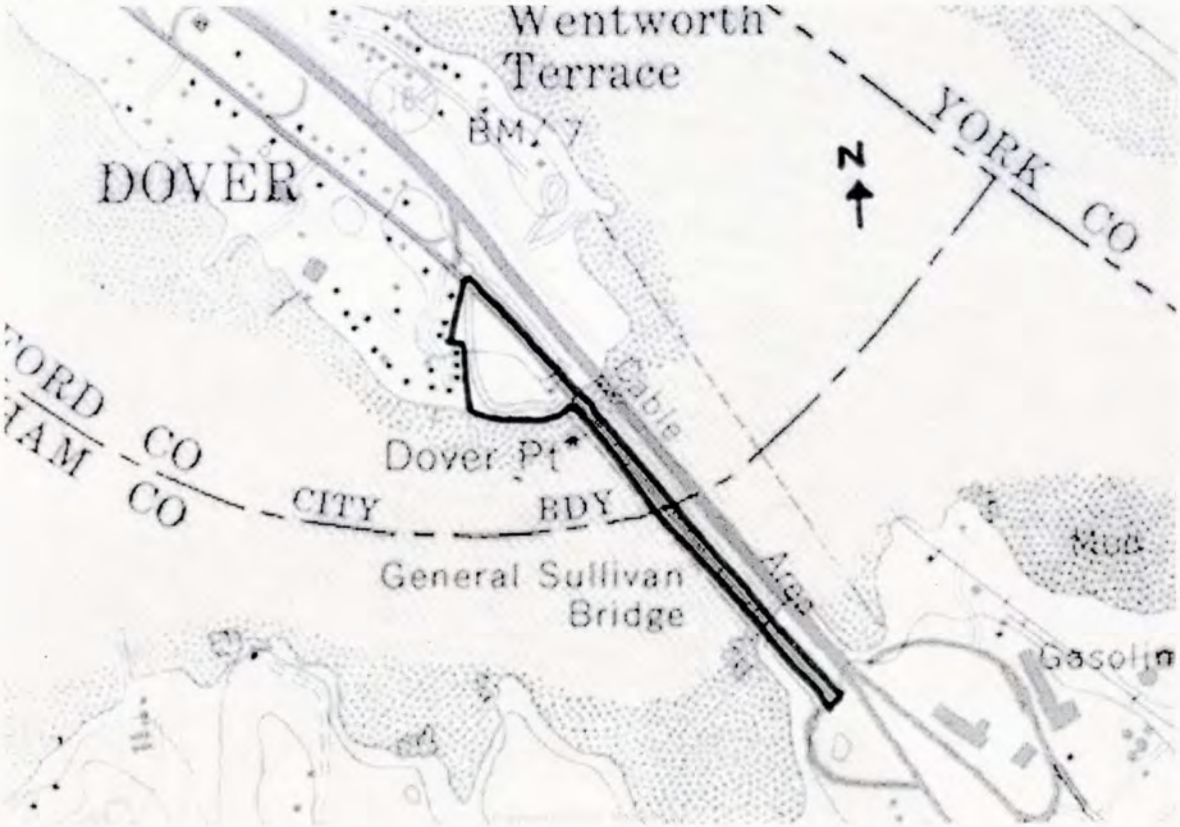
Hilton Park, adjacent to the Dover side of the bridge, although included within the boundaries of this property, is discussed in a separate NHDHR Inventory Form (DOV0150).

The state-owned land on the Newington side of the bridge is not included in the boundaries of this property since the land was not improved. Originally, the state amassed land with the intention of creating parks on both sides of the General Sullivan Bridge. On the Newington side, although the land was purchased and structures demolished, no facilities or access roads were ever constructed and the land was allowed to become over grown and wild.

Please see page B1 for correct boundary.

On the Dover side, a park was constructed piecemeal in two sections on the east and west side of the bridge. The west side was the earliest section to be developed with deliberate design intent. Plans show that by 1949 roads, fireplaces, and a picnic shelter had been constructed. The connection between the two halves was not created until 1955 when the shoreline was increased to allow the construction of a road under the Sullivan Bridge. The eastern half was subsequently developed largely in 1965, but was severed from the west with the construction of the Little Bay Bridge in 1966. It is now thoroughly independent from the bridge and the other section of the Park.

The west section of Hilton Park included in this nomination is now inaccessible from all but local traffic. Along with the historic amenities, it offers the best views of the General Sullivan Bridge, and forms an appropriate setting from which to view the bridge. This section could be renamed and dedicated for the interpretation of the bridge.



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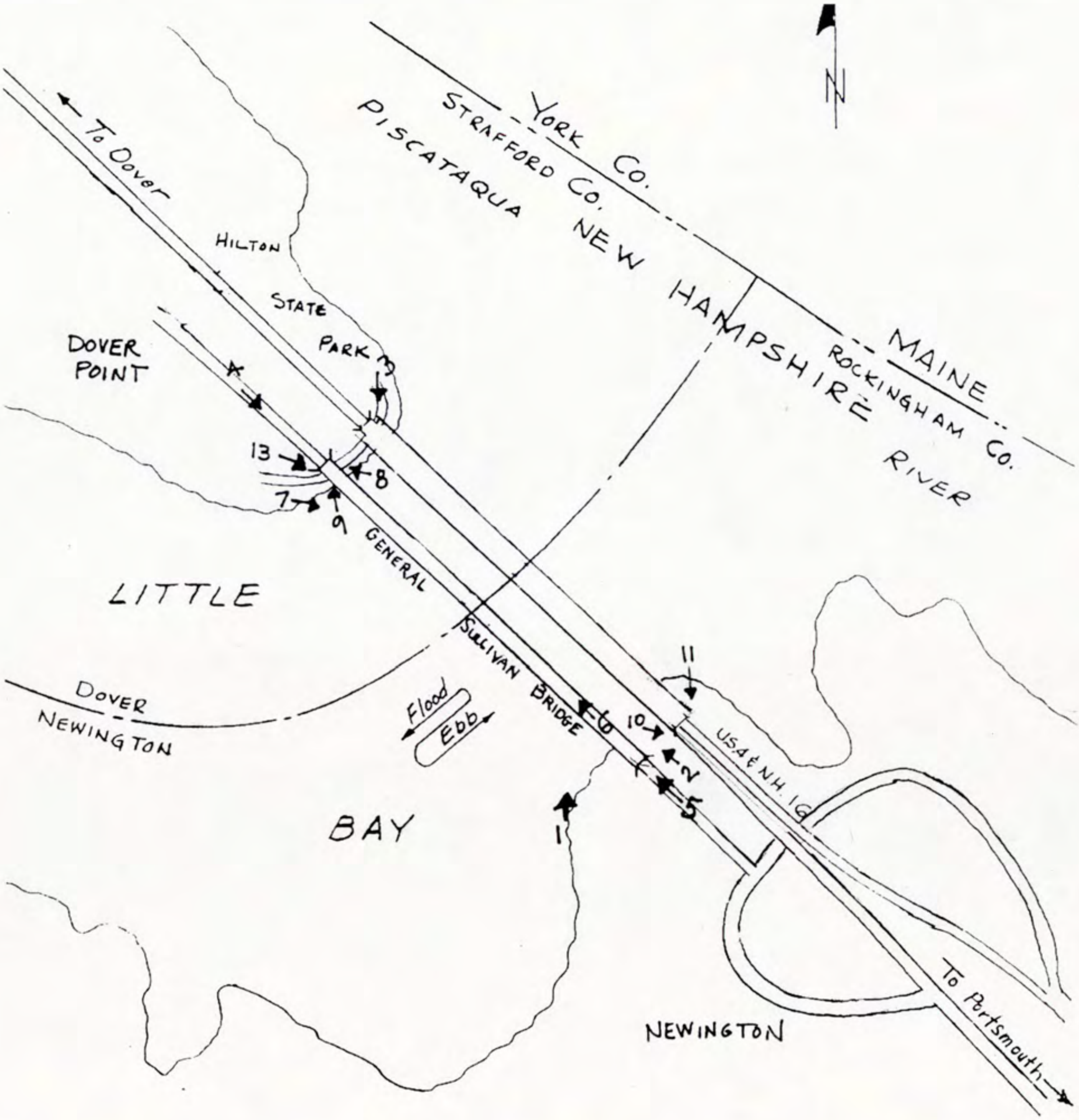
Surveyor's Evaluation

NR listed: individual	☐	NR eligible:		NR Criteria:	A	☒
within district	☐	individual	☒		B	☐
		within district	☐		C	☒
Integrity: yes	☒	not eligible	☐		D	☐
no	☐	more info needed	☐		E	☐

Photo Key


N
To Dover
YORK CO.
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RIVER
GENERAL
LITTLE
SULLIVAN
BRIDGE
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Photographs

Address: Routes 16 & 4 at Little Bay Date taken: November, 2004 Negative stored at: NHDHR

Photo 2: East Facade
Roll: 21 Frame: 29 Direction: NW

Photo 3: East Façade Showing New Bridge in Foreground
Roll: 17 Frame: 5 Direction: SW

Address: Routes 16 & 4 at Little Bay Date taken: November, 2004 Negative stored at: NHDHR

Photo 4 North Approach
Roll: 20 Frame: 32 Direction: South

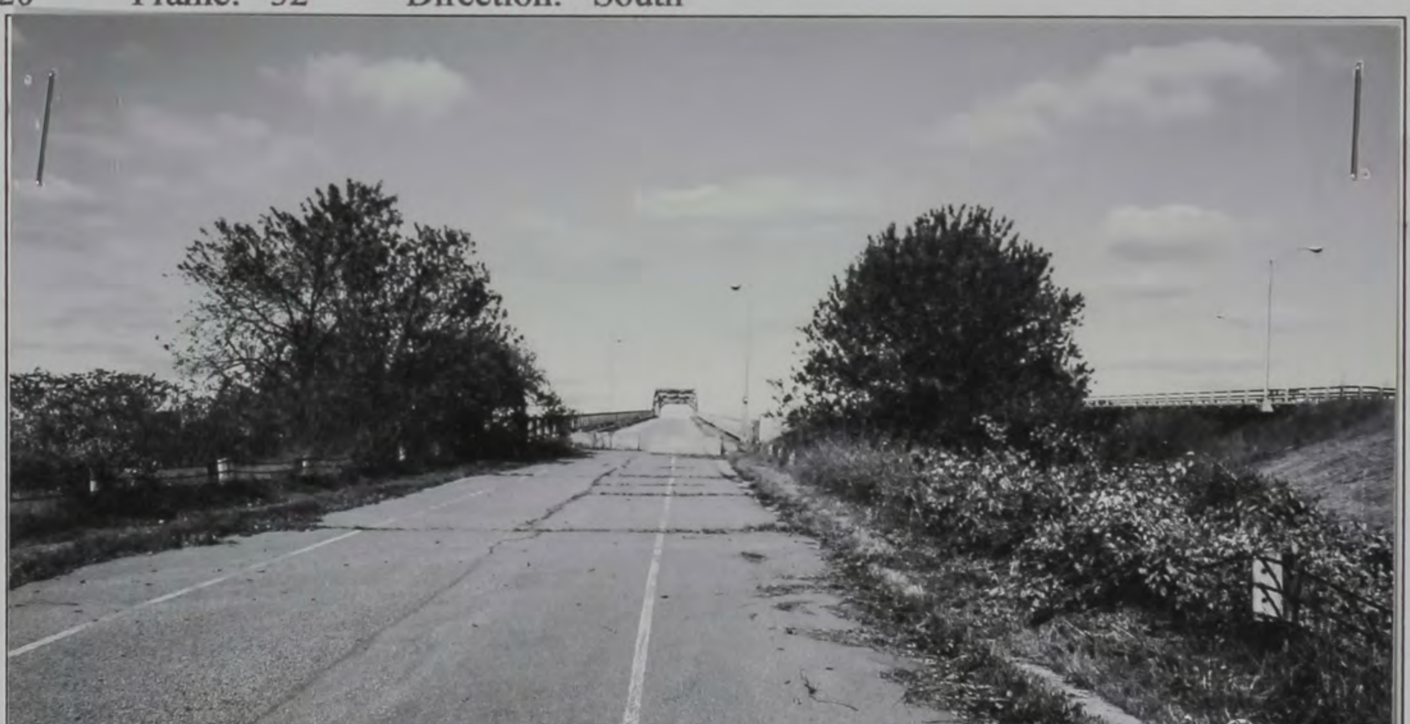

Photo 5 South Approach
Roll: 15 Frame: 12 Direction: N

Address: Routes 16 & 4 at Little Bay Date taken: November 2004 Negative stored at: NHDHR

Photo 6 View of Superstructure
Roll: 15 Frame: 17 Direction: North

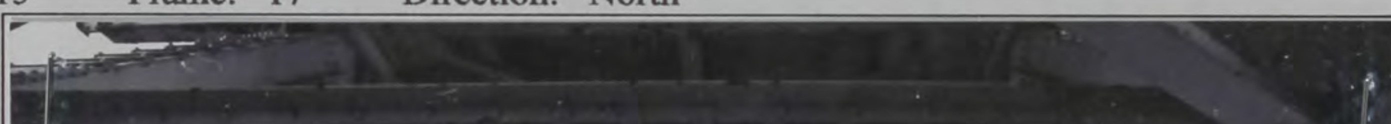

Photo 7 View of Pier
Roll: 20 Frame: 28 Direction: South

Address: Routes 16 & 4 at Little Bay Date taken: October 2005 Negative stored at: NHDHR

Photo 8 View of Side Elevation of Dover Abutment
Roll: 2005-11 Frame: 21 Direction: NW

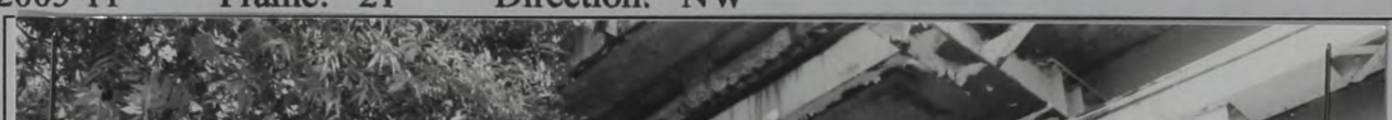

Photo 9 View of Water Elevation of Dover Abutment
Roll: 2005-11 Frame: 24 Direction: N----

Address: Routes 16 & 4 at Little Bay Date taken: November, 2004 Negative stored at: NHDHR

Photo 10: View of Side Elevation of Dover Abutment
Roll: 2005-11 Frame: 23 Direction: NW

Photo 11: View of Side Elevation of Newington Abutment
Roll: 2005-11 Frame: 15 Direction: NW

Address: Routes 16 & 4 at Little Bay Date taken: November, 2004 Negative stored at: NHDHR

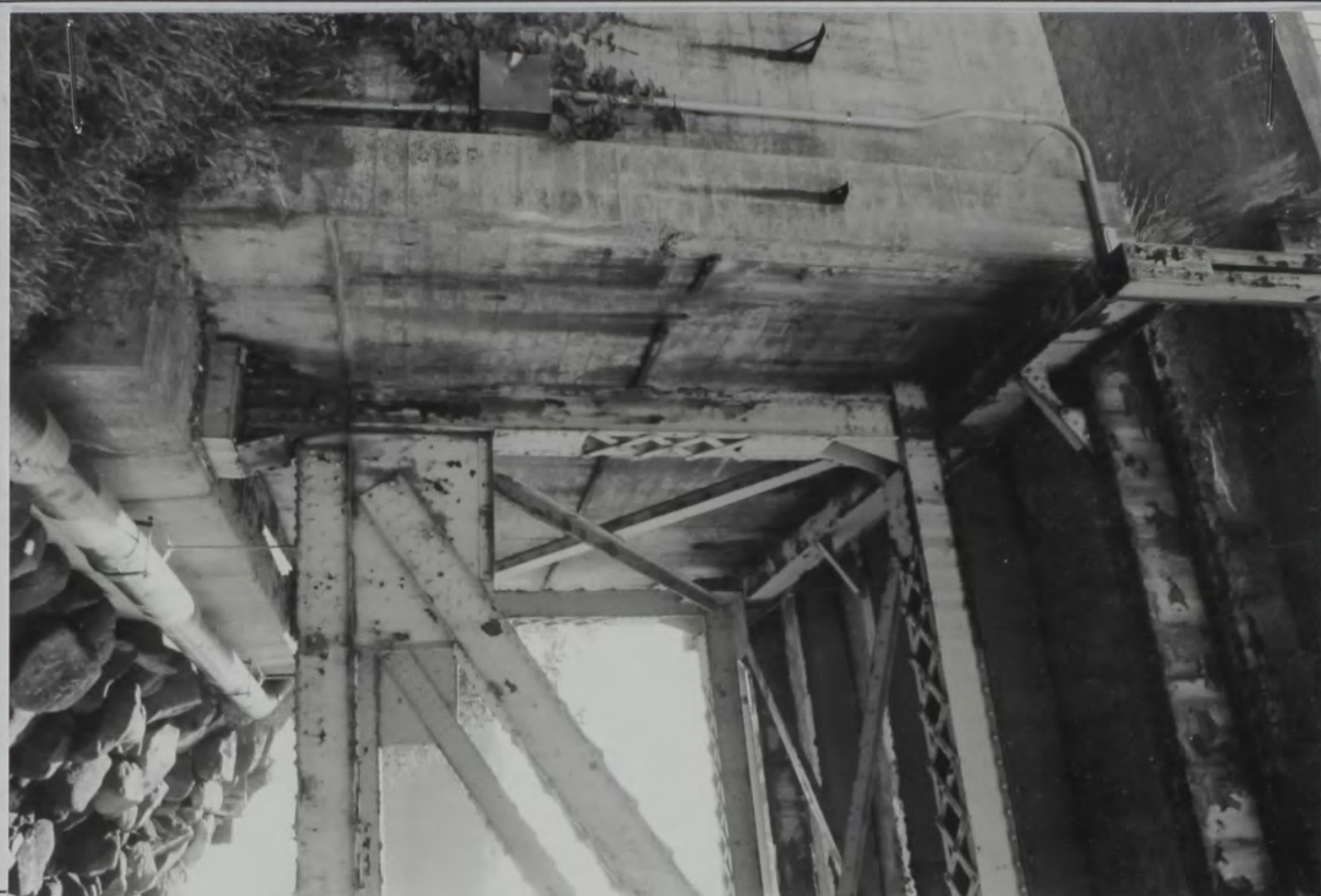

Photo 12: View of Front and Side Elevation of Newington Abutment
Roll: 2005-11 Frame: 11 Direction: S

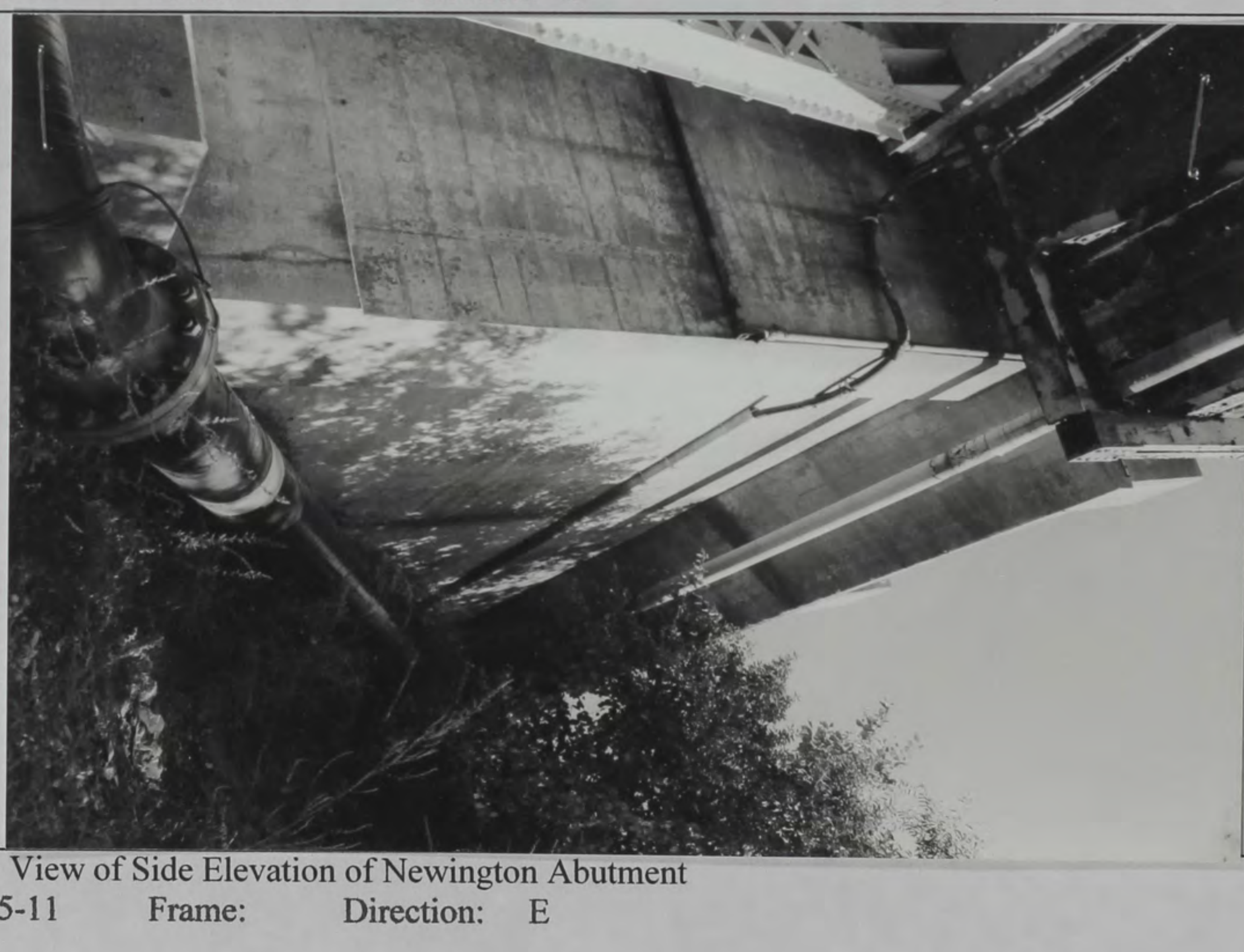

Photo 13: View of Side Elevation of Newington Abutment
Roll: 2005-11 Frame: Direction: E

Address: Routes 16 & 4 at Little Bay Date taken: November, 2004 Negative stored at: NHDHR

Photo 14: Detail of Rocker Bearing
Roll: 2005-11 Frame: 14 Direction:

Photo 15: Plaque
Roll: 13 Frame: 13 Direction: ----

Plans and Drawings for Engineering Context

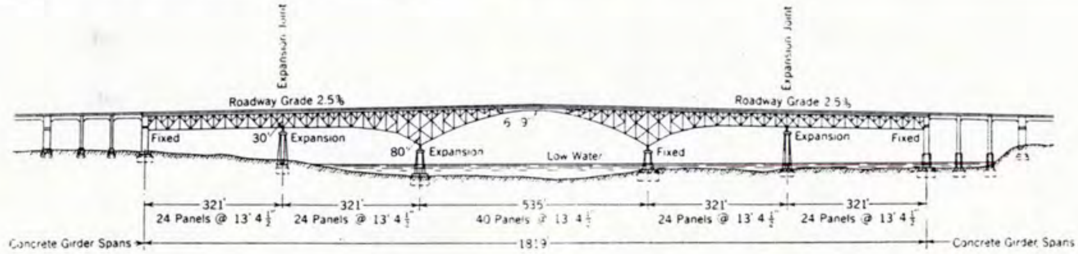

Figure 1: Ross Island Bridge, Portland, Oregon, 1927
main span 535', vert. clearance 100', continuous unit 1177', l.o.a. 1819'

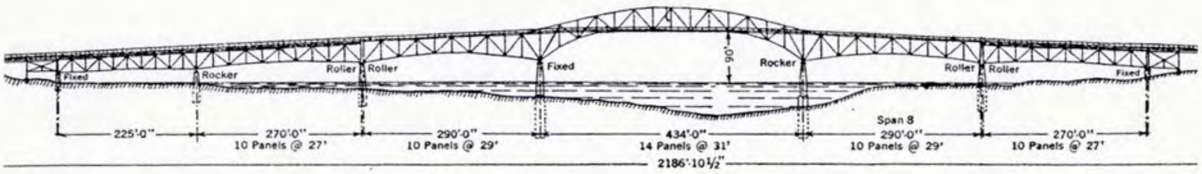

Figure 2: Lake Champlain Bridge, New York to Vermont, 1928
main span 434', vert. clearance 90', continuous unit 1014', l.o.a. 2187'

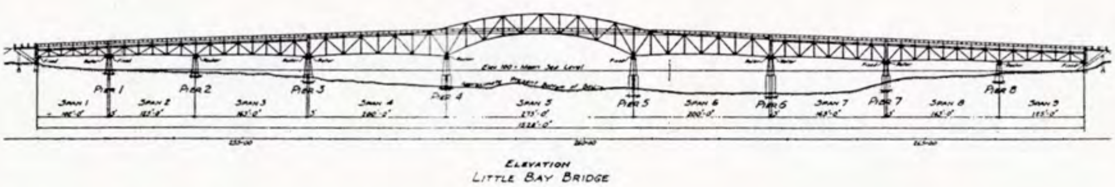

Figure 3: General Sullivan Bridge, Dover, New Hampshire, 1934
main span 275', vert. clearance 40', continuous unit 675', l.o.a. 1528'

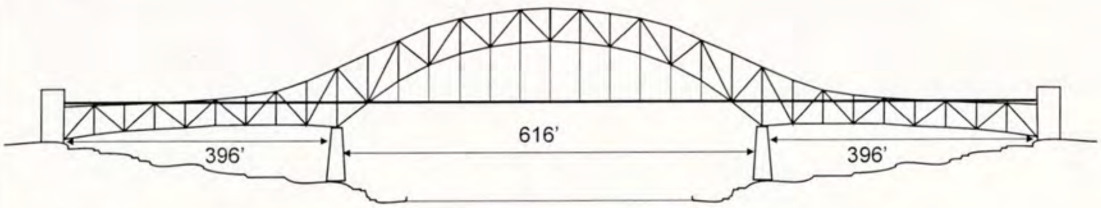

Figure 4: Sagamore Bridge, Cape Cod Canal, Massachusetts, 1935
main span 616', vert. clearance 135', continuous unit 1408', l.o.a. 1408'
Note: Bourne Bridge (1934) identical with addition of two simple deck spans at each end.

Plans and Drawings for Engineering Context (continued)

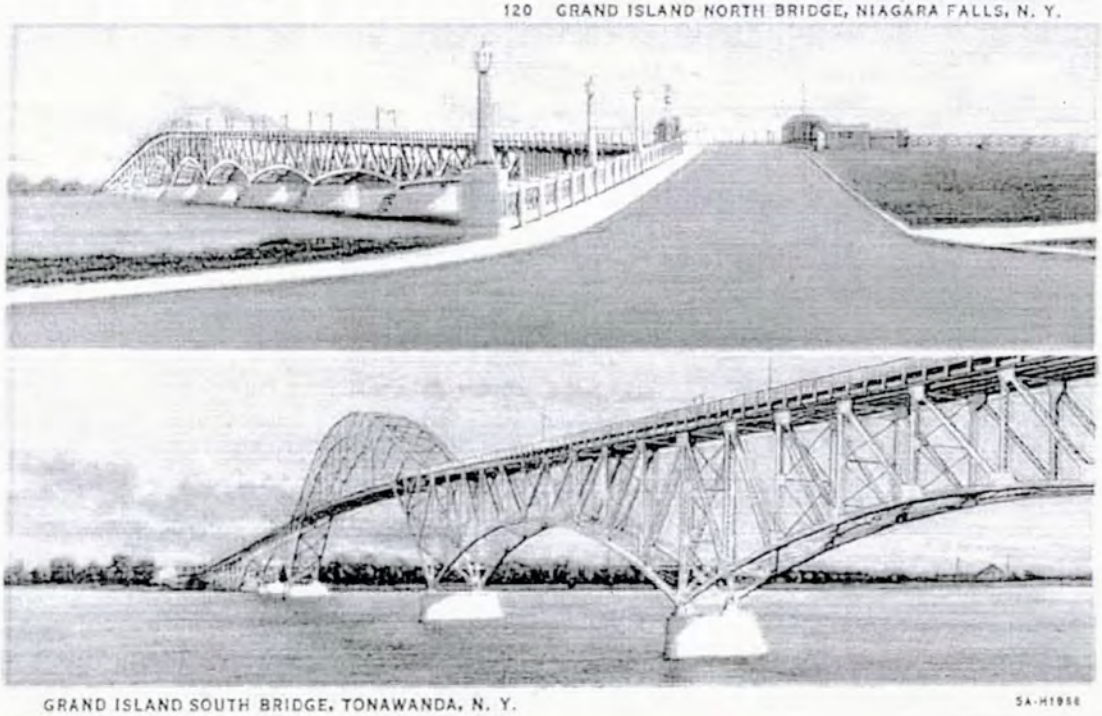

Figure 5: Grand Island, New York Bridges, 1935
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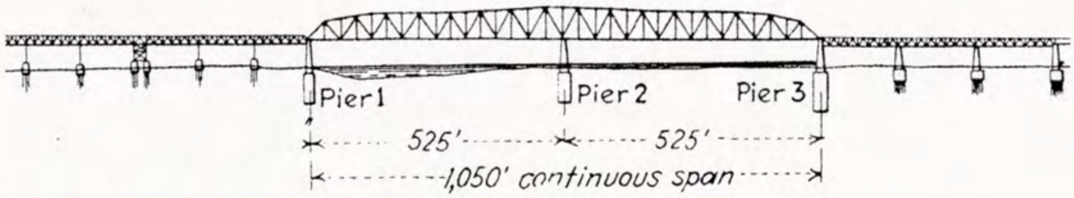


Figure 6: Missouri River Bridge, Omaha, Nebraska, 1935
main span 525', vert. clearance 49', continuous unit 1050', l.o.a. 4378'

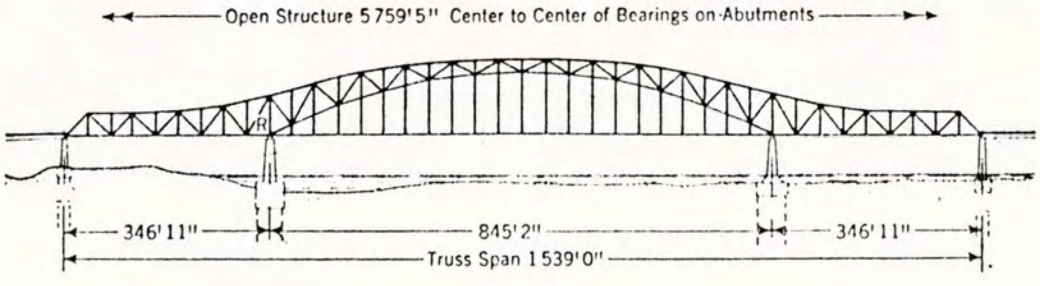
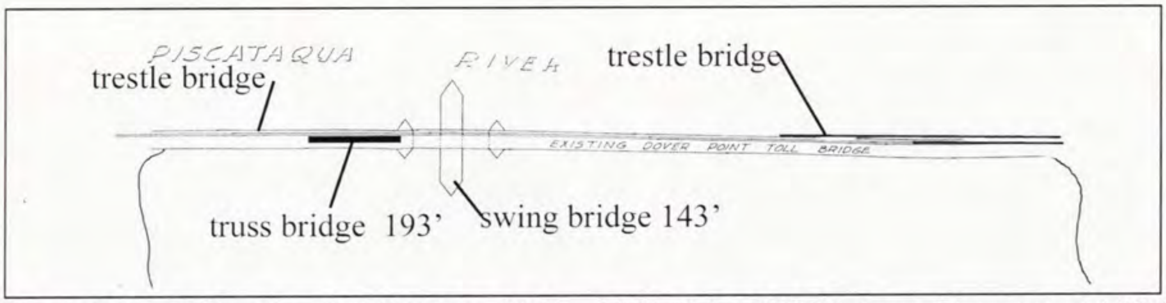


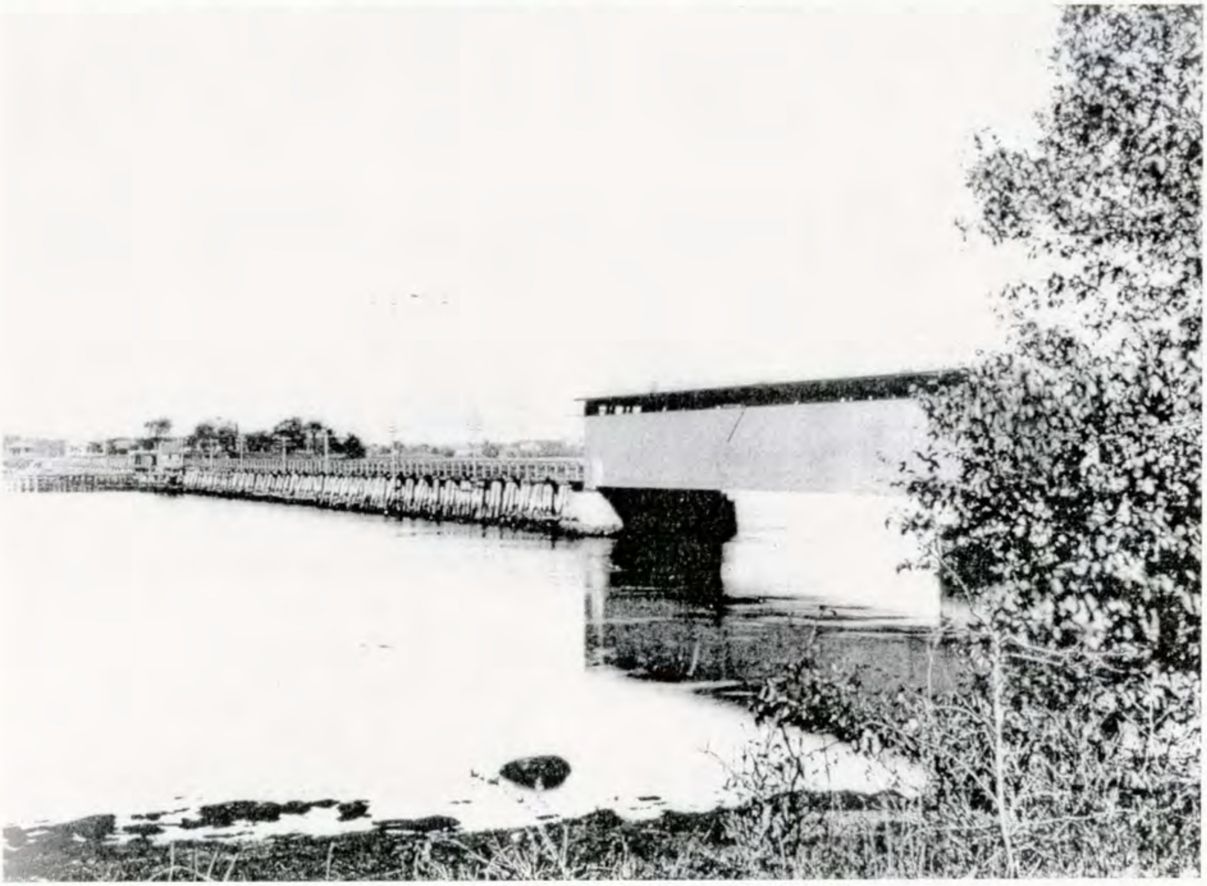
Figure 7: Mississippi River bridge at Dubuque Iowa, 1949
main span 845', vert. clearance 64', continuous unit 1539', l.o.a. 5760'

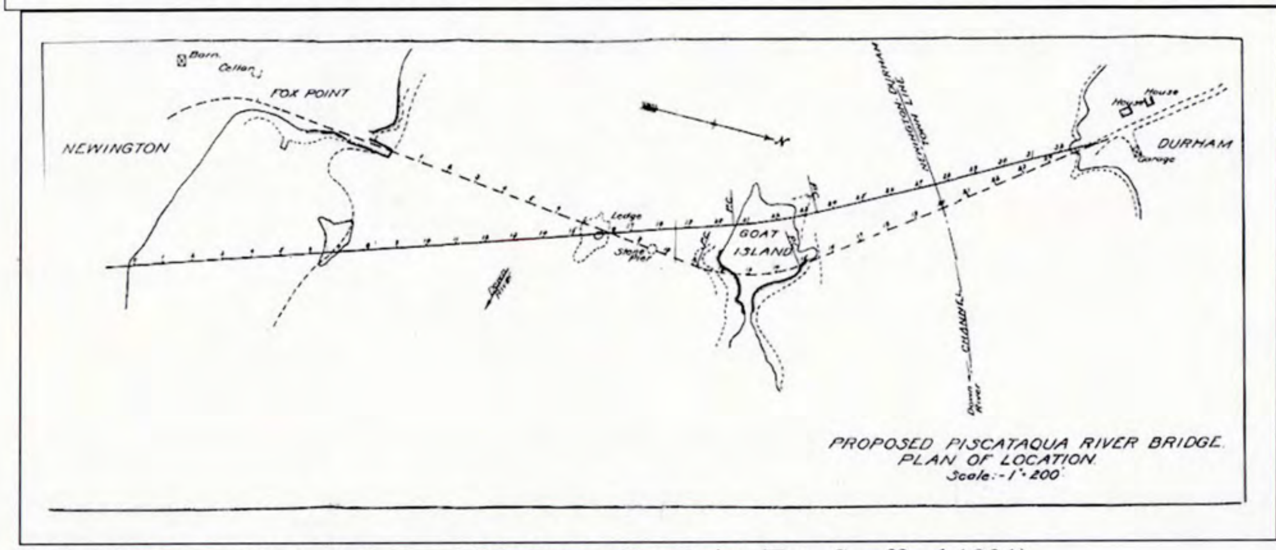
Historic Photos and Plans – General Sullivan Bridge and Area


Piscataqua Bridge [Fox Point] (Gilmor sketch)

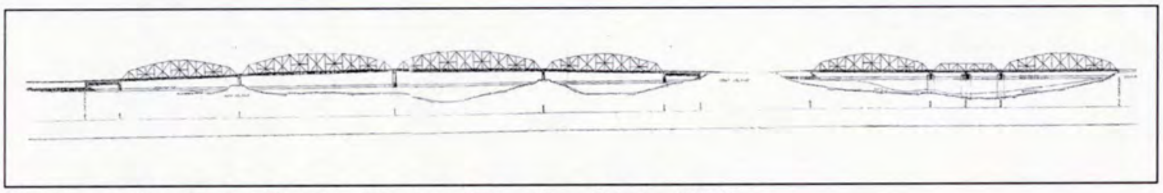


Dover Point Railroad and Toll Bridge 1873 – 1935 (After NH Highway Department 1929)

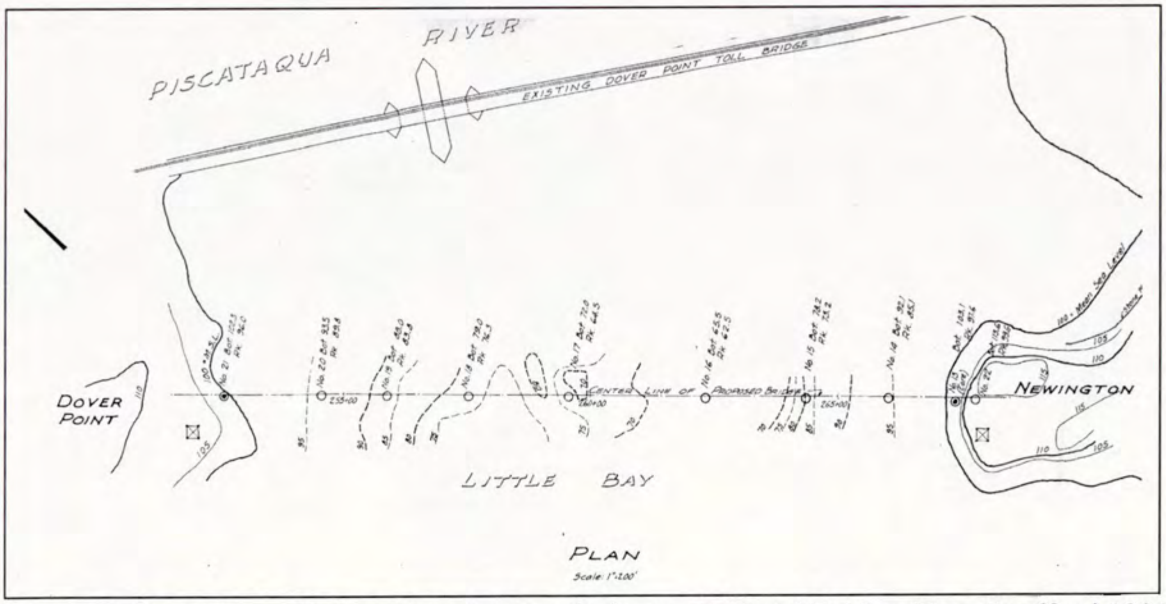

Dover Point [B & M] Railroad and Toll Bridge (Adams 1976:135)



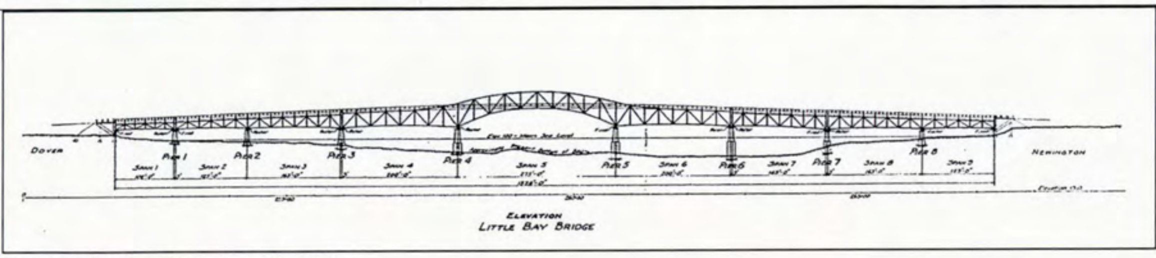
Old and Proposed Routes Across Little Bay at Fox Point (Fay, Spofford 1931)



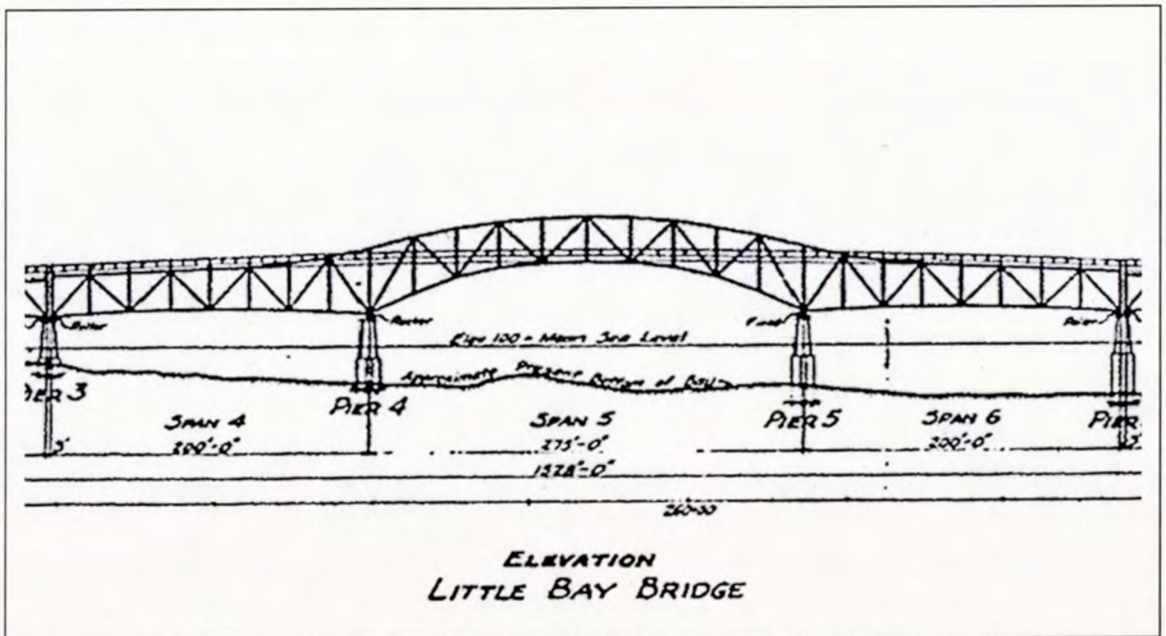
Proposed Fox Point Bridge Design (Fay, Spofford 1931)



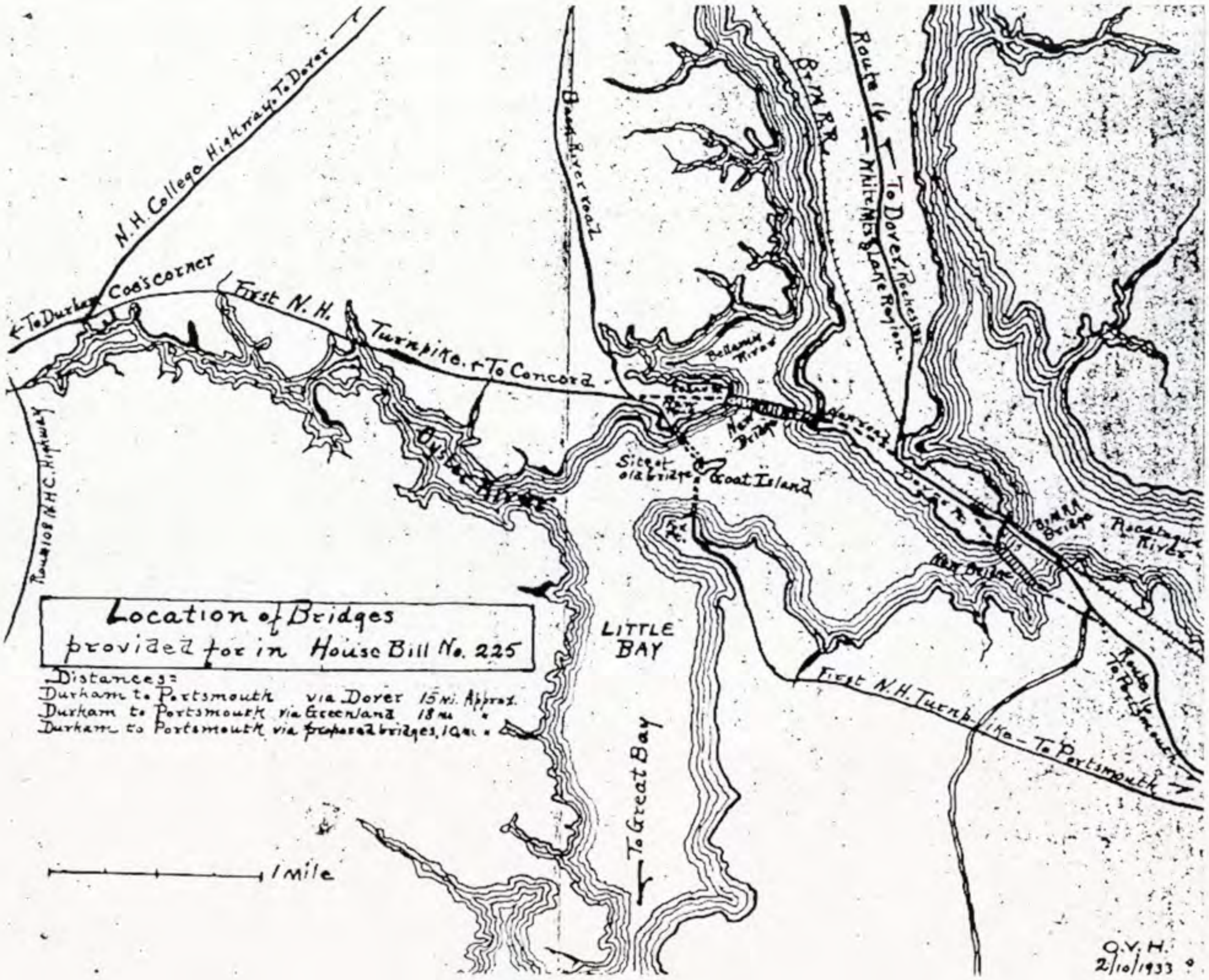
Proposed Dover Point Bridge Showing Proximity to Railroad Bridge (Fay, Spofford 1931)



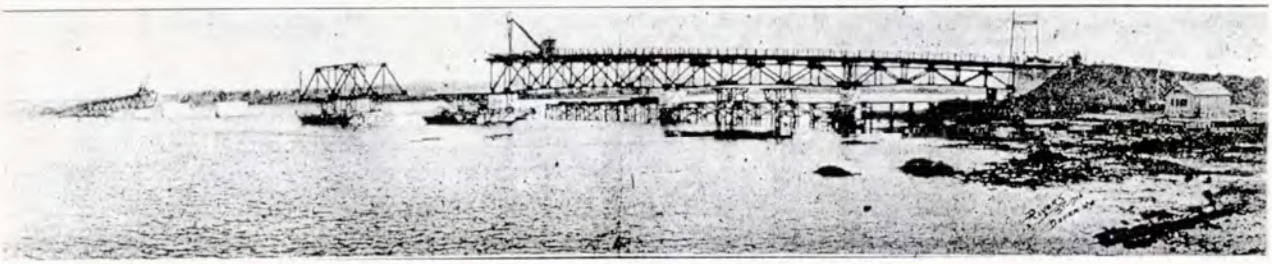
Dover Point Bridge Profile
Elevation Little Bay Bridge (NHDOT)



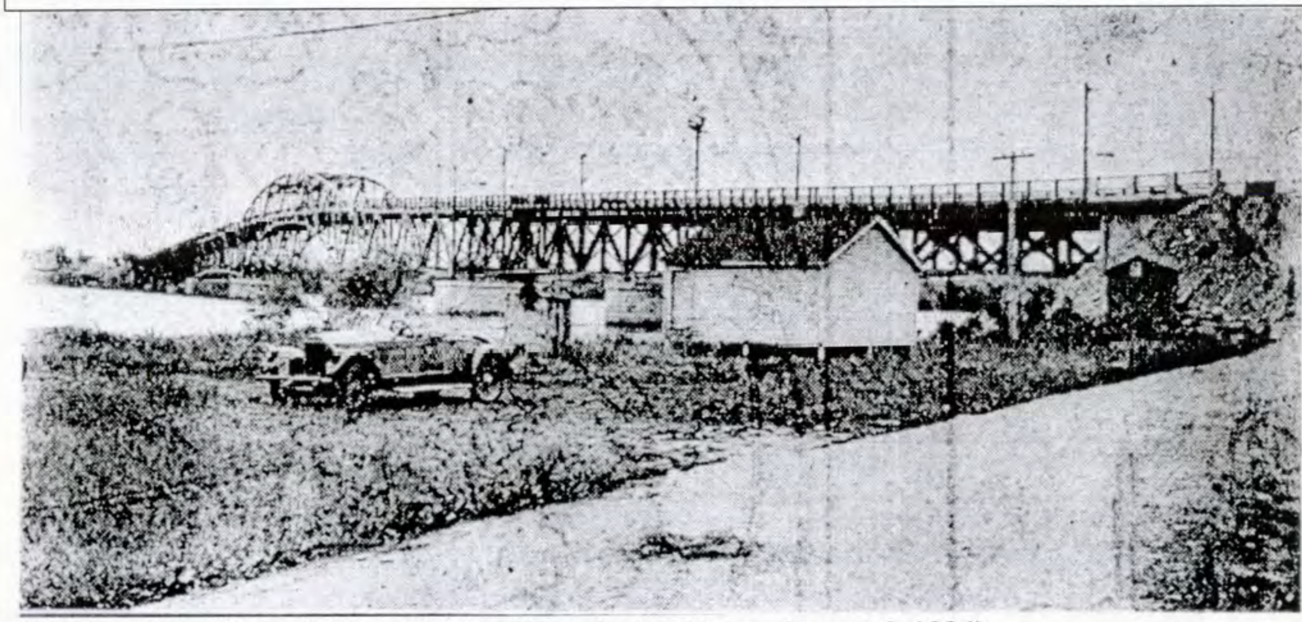
Three-Span Continuous Portion of Bridge, spans #4, #5, #6 (NHDOT)



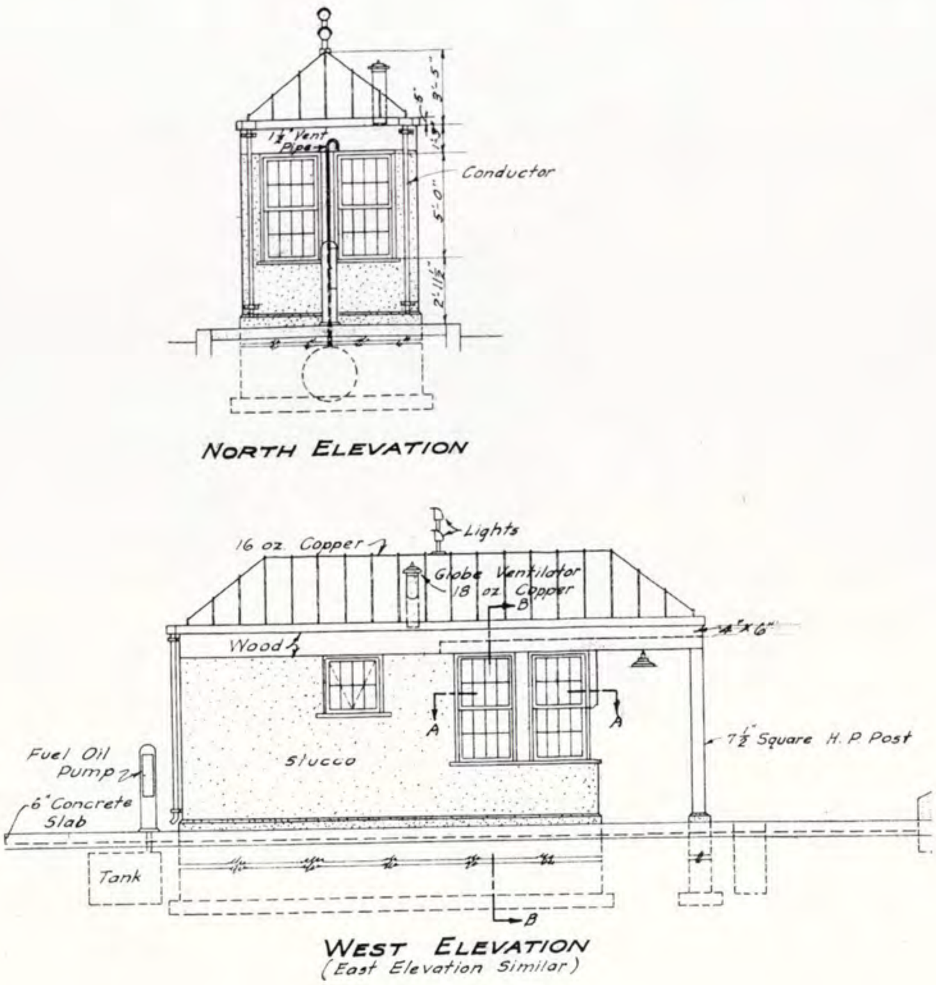
Henderson map showing location of Gen. Sullivan and Scammell Bridges (Henderson 1936)



Construction of Gen. Sullivan Bridge (*Dover Tribune*, May 31, 1934)



Construction of Gen. Sullivan Bridge (*Manchester Union*, August 6, 1934)



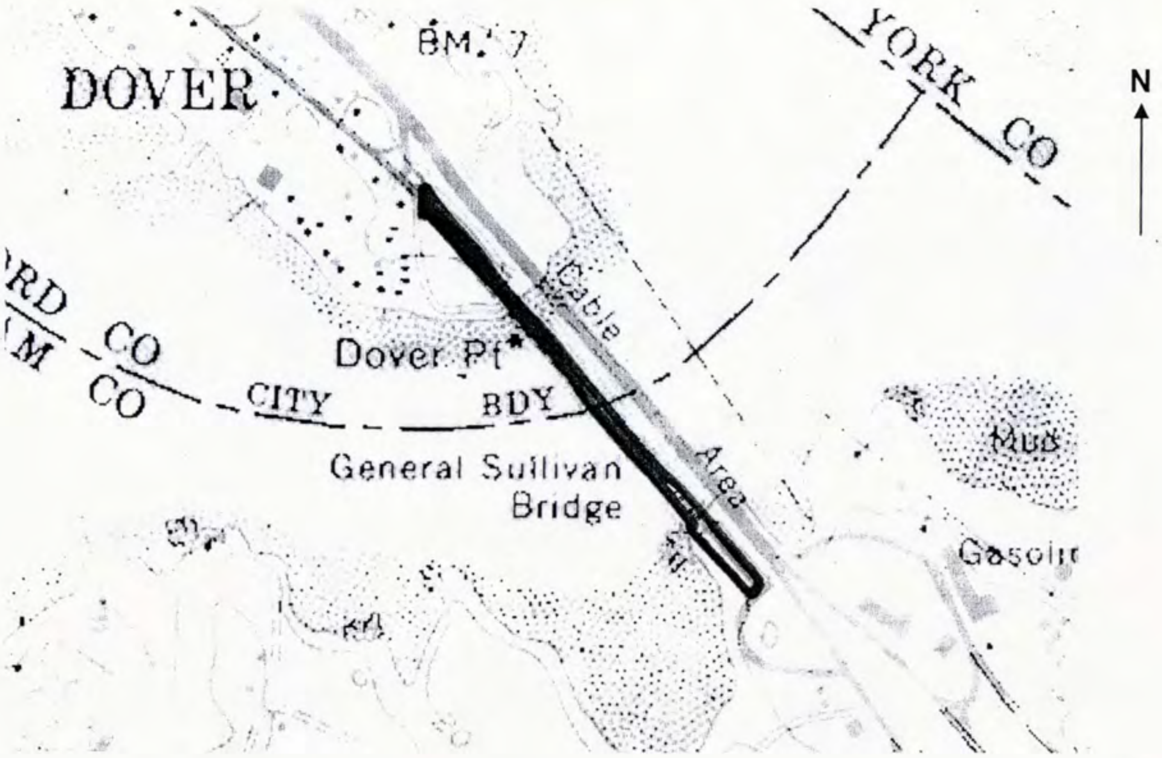
General Sullivan Toll Booth (demolished ca. 1949) (NHDOT 1934) recd 1/19/06

Addendum/Revision January 2006

General Sullivan Bridge

47. Boundary Discussion:

The area covered in this nomination includes the footprint of the bridge itself, its abutments, and approach roads, which was acquired to provide an appropriate setting for the bridge. The boundaries include approximately 2.5 acres.



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GENERAL SULLIVAN BRIDGE

Prepared by the New Hampshire Division of Historical Resources, August 2003

The General Sullivan Bridge, linking Bloody Point in Newington with Dover Point, opened in 1934 as the keystone of a project that was then regarded as "the most unique and outstanding along the line of bridge and highway construction that has ever been proposed in the history of the State."

In design and function, the Sullivan Bridge consciously paid tribute to New Hampshire's transportation history while accommodating the needs of the automobile. Completion of the bridge reopened a portion of a historic but long bypassed route between Portsmouth and Concord. The structure itself was an engineering masterpiece that incorporated the most sophisticated structural design of its era while echoing the graceful form of the "great arch of the Piscataqua," a celebrated wooden span of 1794 that had stood nearby.

Until the Sullivan Bridge opened, all traffic from Portsmouth to Concord traveled first to Dover, then proceeded west through Barrington on Route 9 to join the New Hampshire Turnpike Road (Route 4) in Northwood. The Sullivan Bridge and a companion structure, the Scammell Bridge, provided a new connection with the eastern end of the old turnpike at Cedar Point in Durham. Conducting traffic along the old route through Durham, Lee, and Nottingham, the bridge thus restored usefulness to the full length of the turnpike, which had been chartered in 1796 as the state's first improved highway.

The General Sullivan Bridge was the first span in New Hampshire to be designed as a continuous arched truss, without structural breaks at its supporting piers. This design employed newly developed sophistication in analyzing stresses in continuous structures. Design and construction of the bridge were noteworthy achievements, described in articles in engineering journals of the time. Construction was made difficult by some of the strongest tidal currents in New England and by severe wintertime cold. At one point, flooding and ice floes carried away the timber construction causeways on the Newington shore.

To allow the passage of vessels under the bridge, the top and bottom chords of the center span were arched, giving the bridge a distinct resemblance to its famous timber predecessor, the Piscataqua Bridge of 1794. The Sullivan Bridge has a clearance under its bottom chord of fifty-three feet at low tide, designed to permit passage of tugboats and cargoes up the navigable Lamprey and Squamscott Rivers, as was required by the federal War Department when the bridge was constructed.

The General Sullivan Bridge was designed by Fay, Spofford and Thorndike, bridge design specialists from Boston. Founded in 1914, this partnership was one of the most prolific American bridge engineering firms of the 1920s and 1930s. In 1929, Fay, Spofford and Thorndike had designed a direct prototype for the Sullivan Bridge—the Lake Champlain Bridge, between Chimney Point in Addison, Vermont, and Fort Frederick at Crown Point, New York. In 1935, the firm designed the acclaimed Sagamore and Bourne Bridges over the Cape Cod Canal in Massachusetts, also continuous-truss structures.

When New Hampshire's bridges were evaluated for historical and engineering significance in 1982, the General Sullivan Bridge attained a numerical score of 28 points, one of the highest rankings achieved by any New Hampshire bridge. A score of sixteen points or higher designated a bridge as eligible for listing in the National Register of Historic Places. Sverdrup & Parcel and Associates, the consulting engineers who carried out the bridge evaluation for the New Hampshire Department of Transportation and the Federal Highway Administration, assigned Level I significance to the bridge. Level I indicates that a bridge "is of primary historical significance and merits total preservation, *in situ* [on its original site]."

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NATIONAL HISTORIC CONTEXT AND SIGNIFICANCE OF THE GENERAL SULLIVAN BRIDGE

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October, 2005

NATIONAL HISTORIC CONTEXT AND SIGNIFICANCE OF THE GENERAL SULLIVAN BRIDGE

Summary

Research has identified and defined the early development period of continuous truss highway bridges in the United States as being from 1927 to 1937. This period was preceded by a ten-year period beginning in 1917 during which time the continuous truss highway bridge was developed.

The General Sullivan Bridge is one of four major bridges of the same type, style and time period designed by the firm of Fay, Spofford and Thorndike, that as a group significantly influenced future continuous truss highway bridge design in the areas of technology, aesthetics and construction methods. Fay, Spofford and Thorndike (FS&T) remains in business today and since forming in 1914 established itself as a bridge engineering firm of national importance.

A significant advancement in the technology and aesthetics of continuous truss highway bridge design came with the building of the Lake Champlain Bridge and the three other bridges in which the original design was refined and improved upon.

The Lake Champlain Bridge, completed in 1928, was the third major continuous truss highway bridge built in the U.S. It was a highly innovative and aesthetic design that placed the roadway above the side trusses and through an arched center truss. The design was called "ingenious" for its deck layout that "provided the necessary clearance at mid-span with such economy in the approaches." [1]

The second bridge of the group was the Little Bay Bridge, completed in 1934 and later renamed the General Sullivan Bridge. It represents an important step in the evolution of the continuous truss highway bridge for three reasons: it incorporated special features of the lake Champlain prototype that were proved economically sound; the practical application of a new technology for weighing bridge reactions was demonstrated in its construction; and it established, or helped establish, a markedly reduced economical span length for the continuous truss.

The third and forth bridges of the group were identical and built to span the newly widened Cape Cod Canal. The Bourne Bridge (1934) and Sagamore Bridge (1935) utilized high-strength silicon steel to establish a new long-span length for their design, just 11 feet shy of the U.S. record. The longer span required a deeper truss and taller arch from which the roadway deck was suspended.

The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T proved to be a highly successful solution for large and small highway bridges around the country where aesthetics and the cantilever construction method were necessary factors and was copied for years to come.

The General Sullivan Bridge is an important early example of a continuous truss highway bridge in the U.S. and its design and construction contributed significantly to the advancement of 20th century American bridge technology.

Continuous Truss Railroad Bridges

The use of continuous trusses for highway bridges in the U.S. did not begin until the mid-1920s. Prior to that time, only a few large continuous truss bridges had been constructed to carry railroads over large rivers and with one exception, all dated from 1917 or later. For obvious reasons the great advances in American bridge technology during the late 19th and early 20th centuries were primarily the work of the railroads.

Most historical engineering texts and papers credit the introduction of the continuous truss bridge to America to 19th century railway bridge engineer, Charles Shaler Smith. The Lachine Bridge, designed by Smith and built 1887-1888 to carry the Canadian Pacific Railway over the St. Lawrence River near Montreal, was a monumental structure with two central thru-spans of 408' each and two side spans of 269' each.[2] The Lachine Bridge was considered to be the only continuous truss of "any importance" built in America until 1915 when construction began on the Sciotoville Bridge to carry the Chesapeake and Ohio Northern Railroad over Ohio River.[3]

The Sciotoville Bridge was designed by Gustav Lindenthal, a brilliant Austrian-born engineer who came to America in 1874, built several of the country's greatest bridges including the highly acclaimed Hell Gate Arch Bridge, and ultimately became known as the "Dean of American Bridge Engineers."[4] When completed in 1917, the Sciotoville Bridge - with two continuous spans of 775' each – was the longest and heaviest fully riveted truss in the world, a title it retained until the building of the 839' Duisberg Bridge in Germany in 1935.[5] Through his works and his writings, Lindenthal became a leading authority and proponent of the continuous truss bridge right up to his death in 1935.

Articles on the Sciotoville Bridge in engineering journals led to further interest in the continuous truss type.[6] A detailed series of articles on the building of the bridge by C. B. Pyle, field engineer for McClintic-Marshall Company, the fabricator and erector of the bridge, furthered the understanding of the practical technicalities involved in their construction.[7] The American Bridge Company, McClintic-Marshall's larger competitor, embarked on their own continuous-truss research and development project, and in 1918 designed and completed the second major bridge of the type in the U.S. to carry the Bessemer & Lake Erie Railroad over Allegheny River at Pittsburgh.[8] The Bessemer and Lake Erie Bridge consisted of two 3-span continuous units, the longest span being 520 feet. Also in 1918, Canadian engineers completed the Hudson Bay Railway Bridge over the Nelson River in Manitoba with a 400' center span and two 300' side spans.[9]

Discussion of the economical applications of continuous bridges and the analysis of indeterminate structures and secondary stresses followed these pioneering structures and continued through the 1920s and into the 1930s. Papers and textbooks on the subject were published by many of the leading engineering professors and practitioners.[10]

Lindenthal's detailed account of the design of the Sciotoville Bridge in the *Transactions of the American Society of Civil Engineers* garnered comments from such learned engineers of the day as C.A.P. Turner, J.E. Greiner and D.B. Steinman.[11] Most debate hinged on the economy of continuous versus simple span truss designs because Lindenthal had not only advocated the continuous span in place of the long-span cantilever, but also as an economic alternative to simple truss spans in many lesser-span situations. After a lengthy and detailed argument, Professor Turner found that while Lindenthal "discloses meritorious details in advance of current practice," his conclusion on the economical virtues of the continuous truss for moderate spans "differs from the majority opinion of American bridge engineers because of lack of demonstrated economy on a scientific mathematical or design basis."[12]

Lindenthal effectively rebutted Turner's economic argument by explaining that the added stiffness and greater resistance to impact and wind loads afforded not only by the continuous girders, but by the continuous lateral bracing, produced a better bridge better suited for high levels, high wind areas and high speed traffic, and would prove economical in that respect not only for moderate but shorter spans as well.[13]

Steinman was squarely in Lindenthal's camp, calling the continuous truss "an excellent bridge type, offering decided advantages (under suitable conditions) over practically all other forms of construction...its general adoption for fixed spans has long been retarded by prejudices based on erroneous notions...a proper comparison with corresponding simple spans will generally show a substantial saving of material in favor of the continuous structure."[14]

Another landmark paper which provoked extensive discussion and much acclaim was entitled "Secondary Stresses in Bridges" by Cecil von Abo published in 1926.[15] Abo compared the various methods pertaining to secondary stresses, applying each to a 150' Warren truss railroad bridge. The ensuing discussion again showed fundamental and complex disagreement among engineers as to the preferred method of solving for secondary stresses and even the importance of doing so.

Continuous Truss Highway Bridges

Lindenthal again led the way with what is apparently the first modern continuous truss highway bridge of indeterminate design in the U.S. of significance, the Ross Island Bridge over the Willamette River in Portland, Oregon completed in 1927 **(Figure 1)**. The Ross Island Bridge incorporated an arched center span of 535' and half-arched side spans of 321' with a concrete slab roadway carried above.[16] Lindenthal completed another continuous truss highway bridge over the Willamette in Portland in 1927 as part of the same commission, the Sellwood Bridge. It was also a deck bridge but with parallel-chord trusses and a maximum span of 300 feet. Lindenthal built two continuous truss highway bridges of determinate design in 1880 and 1890 based on the counterweighted funicular principal, see note.[17]

The Ross Island and Sellwood bridges did not receive major coverage in the engineering literature at the time of their completion. One small article discussed the unique method of closing the arch of the Ross Island Bridge without jacking that instead utilized the careful calculation of the expansion of the steel truss due to the daily temperature change.[18]

Lake Champlain Bridge

Following right on the heels of Lindenthal was the engineering firm of Fay, Spofford & Thorndike (FS&T) who in 1927 began the design of a long-span continuous arched truss bridge to span Lake Champlain. The bridge was an innovative and highly aesthetic design with the roadway deck carried above the side trusses and through the arched center truss (**Figure 2**). The bridge was called "ingenious" for its deck layout that "provided the necessary clearance at mid-span with such economy in the approaches."[19] Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike were all highly accomplished bridge engineers and their firm's bold design must have been partly driven by a desire to establish prominence in the rapidly expanding field of long-span highway bridge design.

It was agreed at the outset by both the engineers and the owner (Joint [Bridge] Commission of New York & Vermont) that the bridge "should have as pleasing an appearance as possible" due to its conspicuous height and the historic importance of the site.[20] In designing the Lake Champlain Bridge, Spofford states that he "found it impossible to sketch any simple span design that was at all satisfactory in appearance."[21] He also considered cantilevered and suspension bridges, but discounted each for various reasons, settling finally on the continuous type, which he decided "can be given a more pleasing appearance, consistent with economy, than any of the other types of truss bridges."[22] Design of the Lake Champlain Bridge was begun August 2, 1927 and the final plans accepted November 15, 1927.[23] This places the FS&T design at the very forefront of continuous truss highway bridge construction in the U.S.

Steel Bridge Aesthetics & Further Development

The innovative and highly successful integration of aesthetics into long-span truss design by Fay, Spofford & Thorndike was a significant development. American bridge engineering treatises have included extensive sections on the aesthetic design of bridges since the late 19th century. Bridge designers were instructed to consider the fundamental principles of artistic design in the order of their importance: symmetry, style, form, dimensions, and ornamentation. Occasional commentaries on the elements of good aesthetic design and beauty as it pertained to bridges appeared in the engineering press in the early 20th century, but it was during the 1920s that the movement picked up considerable speed, coinciding with the larger societal movements toward aesthetically designed public spaces like the City Beautiful movement.

The divergent opinions that existed regarding bridge "architecture" and aesthetics came to light in 1920 following a story in *Engineering News Record* about a highly decorated concrete bridge built in Philadelphia.[24] A war was waged in a series of articles, editorials and letters over the relationship between art and structures and between architects and engineers, and over who was more qualified to judge what is aesthetically pleasing.[25] Foremost among the causes of the dispute, was the rapid development and adoption of reinforced concrete bridges for the nation's expanding highway network. Moldable into virtually any shape or form, economical, and well suited to arches, concrete at first ushered in a nostalgic return to the classicism and heavy decoration found in earlier bridges crafted of stone. But a symbiotic relationship quickly developed between concrete and the new architecture of Modernism, promoted by Frank Lloyd Wright, Le Corbusier, Mies van der Rohe and others. Functionality meshed with Machine Age philosophy to become Functionalism expressed in Modernistic concrete bridges. The traditionalists and the progressives were at each other's throats.

Longing for the days of stone, "old school" bridge engineer Gustav Lindenthal weighed in with an article in *Scientific American* in 1921 entitled "Some Aspects of Bridge Architecture."[26] Lindenthal found fault with nearly everything that was happening in the bridge business, but had special vehemence for the current art of steel bridge building: "there is no thought of architecture, or of durability or of pride in the art... the most naked utilitarian considerations are allowed to govern the design... it has become a commercialized trade which has been prostituted, under the pretense of scientific economy, to the production of the cheapest structures that will carry the loads."[27]

Meanwhile, concrete bridge technology gloriously advanced, stretched into long delicate arches or molded into highly stylized Classical, Art Deco and Modern forms. Each year increasingly stupendous and unarguably beautiful concrete bridges were going up. By 1929 the structural steel industry had had enough. The American Institute of Steel Construction (AISC) established an award to be given annually to the "most esthetic solution to a problem in steel construction." The first award was given retroactively to the 6th Street Suspension Bridge in Pittsburgh completed in 1928. For 1929 it was decided to give three awards, one for long span bridges, one short span and one honorable mention, the latter given to the Lake Champlain Bridge.[28]

The AISC's director of engineering services, F.H. Frankland, presented a paper to the Canadian Good Roads Association in 1929 in which he noted that the possibilities for continuous bridge design was now recognized by engineers and continued to gain their favor. The bridge type had "generally come to be accepted as the full equivalent of other types where field erection conditions and economy in material permit."[29] Continuous trusses were increasingly being found more economical than cantilevers for long span highway bridges. The first continuous-truss highway bridge over the Missouri River was designed by the firm Sverdrup and Parcel and completed in 1929 at St. Joseph, Missouri.[30] The bridge had two 450' thru-spans and resembled a cantilever design with panels of varying depth increasing to a maximum over the center pier. The next year the Strauss Engineering Company of Chicago spanned the Mississippi at Quincy, Illinois with a parallel chord truss design that incorporated two-spans of 627' each and established a new record for continuous truss highway bridges.[31] The design of these two bridges demonstrated the potential economy afforded by the type when aesthetic considerations are removed from the equation.

In 1930 the AISC decided to give three awards based on a bridge's cost: Class A, over $1 million; Class B, $250,000-$1 million, and Class C, less than $250,000. The press coined the term "most beautiful steel bridge of the year award" which stuck. The Class B award went to a short-span continuous arched truss deck bridge in Delton, Wisconsin, similar in design to Lindenthal's Ross Island Bridge.[32] Two more continuous arched truss deck bridges received the AISC's awards in 1932: the French King Bridge in Massachusetts (Class B) and the Byran Bridge in Nebraska (Class C).[33]

With all this attention and awards being heaped on continuous trusses, Lindenthal came forward to set the historical record straight on his priority and preeminence in the business with an article in *Civil Engineering* (1932) entitled "Bridges With Continuous Girders; Reviewing Half A Century of Experience in American Practice."[34] Lindenthal described his experiments with funicular bearing bridges in the 19th century (see note 15) but made a special point of mentioning Spofford's 1931 article on the Lake Champlain Bridge, noting, "A similar structure, the Ross Island Bridge, having arched continuous girders, was built under my supervision in 1925-1927."[35]

Little Bay Bridge, later named General John Sullivan Memorial Bridge

The contract for design and construction supervision of the Little Bay Bridge was given to FS&T by the New Hampshire Toll Bridge Commission on April 11, 1933 and by July 27 the plans for the superstructure were complete and advertised for bids (**Figure 3**). Foundation construction began July 27, 1933 and on September 5, 1934 the bridge was opened to traffic.[36] *Engineering News-Record* called the General Sullivan Bridge and the companion Ballamy River trestle bridge "exceptional structures, which are notable in design and particularly for the construction methods employed."[37]

The design mimicked the acclaimed Lake Champlain Bridge with the same innovative arrangement of deck side trusses and arched center thru truss that reduced the height and cost of the approach grades while achieving the necessary high-level channel clearance. The Little Bay Bridge represents an important step in the evolution of the continuous truss highway bridge for three reasons: it incorporated special features of the FS&T prototype that were proved economically sound; the practical application of a new technology for weighing bridge reactions was demonstrated in its construction; and it established, or helped establish, a markedly reduced economical span length for the continuous truss.

Special features

The special features included the innovative deck layout previously discussed, and the use of a state-of-the-art concrete deck design. The slab was reinforced with "welded bar trusses spaced 6 inches between centers and welded into mats by adding spacer bars across the trusses."[38] This is an early use of so-called "unit trusses" for reinforcement, but exactly how early was not determined. Another deck feature was the two-layer construction with the top wearing surface separated from the structural slab by a burlap "cleavage fabric to permit the top layer to be removed if it wears out without disturbing the floor-slab."[39] The design of the dove-tailed sliding-plate deck expansion joints and the double-stepped curbing were also mentioned in the articles on the bridge as being of note.[40]

Technology

Spofford advanced the method of weighing bridge reactions in the field by using newly developed proving rings of unprecedented accuracy to adjust the end reactions on the General Sullivan Bridge.[41] This was the first time the method had been used on a large continuous bridge. Spofford also used the rings on the later Bourne and Sagamore bridges and brought his findings to his colleagues in a 1935 article.[42]

The determination through field measurement of the actual exact weight that a continuous bridge bears down upon each of its supporting bearings is necessary to confirm that the erected structure conforms with its mathematical design. Spofford states that "the assumed reactions at the piers are seldom if ever attained because of such things as changes in the relative elevation of the piers, variations in the modulus of elasticity of built-up steel members, and differences in length of the various truss members as they come from the fabricating shop."[43]

Weighing and adjusting the reactions of continuous bridges was done by Lindenthal and others with hydraulic jacks coupled to pressure gages and with strain gages. Spofford used hydraulic jacks with gages on the Lake Champlain Bridge but found the method to be unsatisfactory due to the inability to measure the friction in the jacks and to maintain the gages in calibration in the field.[44]

The proving rings used by Spofford were patented in the mid-1920s and consisted of round steel "donuts" with sensitive measuring instrumentation inserted within the ring. When a load was placed on the rings its deformation could be measured with extreme accuracy. The proving rings used to measure and adjust the General Sullivan Bridge were manufactured by Morehouse Machine Company of York Pa., and were of 200,000 pound capacity with an accuracy guaranteed to one-tenth of one percent. The rings were actually sensitive enough to detect differences as small a 2 pounds and the operator found he could detect disturbances due to a man standing on the bridge.[45]

The first use of proving rings in bridge construction was in 1933 when David S. Fine, an erecting engineer with the American Bridge Company, used the devices to measure the reactions of a bascule bridge the company built in New Jersey. Spofford was the second to use the rings, and the first to utilize the method for continuous truss construction.[46]

New economical span length

Although overlooked in the engineering literature at the time, the design of the Little Bay Bridge was particularly notable for its main span length of 275' and continuous unit length of 675'. These lengths approached nearly half the length of the Lake Champlain and French King bridges and may have constituted the shortest continuous arched truss built to date. This is significant because in the case of the continuous truss, the trick was to demonstrate that the type could be economically suited for shorter spans, not longer spans. Each type of bridge has a range of span length for which it can be used to advantage over other types, adjusted for variables such as site conditions and loading. In the overall development of highway bridges during the expansion of the nations highway systems, improving the economy and aesthetics of short-to-moderate spans was far more important than the few record setting long-span bridges that garnered the greatest attention. The addition of a very aesthetically appealing truss design that could be built with the cantilever construction method and prove economical for medium span lengths was an important advancement.

Bourne and Sagamore Bridges

The Bourne and Sagamore Bridges were designed by FS&T for the Army Corps of Engineers to span the newly enlarged Cape Cod Canal (**Figure 4**).[47] The Bourne Bridge opened first in 1934 and received the AISC "Class A" award for most beautiful steel bridge of that year; the Sagamore Bridge opened in 1935 and received honorable mention in the Class A category.[48] The three-span continuous arch unit is identical on the two bridges, with the Bourne Bridge additionally equipped with two simple deck-truss approach spans at each end.

With the economical short-span length established for their trademark continuous truss design by the General Sullivan Bridge, the Cape Cod Canal project now presented FS&T the opportunity to establish a new long-span length for their design. At 616', the Bourne and Sagamore spans exceeded the Ross Island Bridge by 81 feet and were just 11' shy of the record span length for a continuous-truss highway bridge apparently set in 1930 by the Quincy Memorial Bridge over the Mississippi River at Quincy, Illinois.[49] These two long bridges however, were still roughly 150' shy of Lindenthal's 1917 Sciotoville railroad bridge.

In addition to the forty-percent increase in span length that the Bourne and Sagamore bridges represented over the Lake Champlain Bridge, they were designed to use high-strength silicon steel. Although the steel cost was 12.8 percent more than ordinary carbon steel, the stronger steel allowed a reduction in the size and cost of the individual members and resulted in a savings of approximately $50,000 for the two bridges.[50] This was not the first use of silicon steel in continuous truss highway bridge construction, at least two other bridges, the 1929 Missouri River Bridge at St. Joseph and the 1930 Quincy Memorial Bridge over the Mississippi made extensive use of it.[51]

The Cape Cod Canal bridges also differ significantly from the Lake Champlain and General Sullivan Bridges in the profile of the arch and the roadway locations, as shown in Figures 2, 3, and 4. The longer span required a deeper truss and taller arch. In order to keep the roadway grades within prescribed limits, the deck was suspended from the arched truss rather than carried at the level of the lower chord members. This arrangement was dictated primarily by site conditions, specifically the required channel clearance opening of 135' high by 500' wide, and the limitations of the possible approach configurations.

End of the Development Period

The mid-1930s appear to mark the end of what can be considered the development period of the continuous truss bridge in the U.S. The type began to see broad use in a wide range of spans and the AISC continued to give the type awards nearly every year. Referring to bridge developments in 1937, A.L. Gemeny, senior structural engineer for the U.S. Bureau of Public Roads said "in the field of steel bridges multiple simple spans have almost gone into discard...continuous beam and girder spans are being generally adopted for intermediate lengths ...for long spans continuous trusses and cantilevers are used."[52]

In 1935 two major bridges designed by the firm of Waddell and Hardesty were completed over the north and south branches of the Niagara River to Grand Island (**Figure 5**). The south bridge was a near copy of the Cape Cod design with a center thru-span and a suspended deck, the north span was a deck bridge. Both Grand Island bridges had more deeply arched side spans than the FS&T designs, which were essentially flat. The north bridge with the deck truss won the AISC "Class A" award for 1935, beating the Sagamore Bridge which received honorable mention.[53]

Non-arched two-span thru-trusses like the 1929 St. Joseph Bridge over the Missouri River and the 1930 Quincy Bridge over the Mississippi continued to be the preferred design for continuous truss bridges over the big mid-west rivers. Two examples are the mile-long Missouri River bridge at Omaha with a 2-span continuous truss of 1050' overall, completed 1935 **(Figure 6)** [54] and the Mississippi River bridge at Hannibal, with a two-span continuous truss 1125' long, completed in 1936.[55] Continuous deck trusses were also seeing more widespread use in approaches to the big river bridges, as shown by the three-span continuous-truss deck units of 222' span that were used as approach spans to the 740' suspension span of the Mississippi River Bridge at Davenport, Iowa.[56]

State highway departments continued to gain confidence in designing continuous bridges in-house. The Kansas Highway Commission adopted continuous spans and built rolled-beam, plate-girder and continuous truss bridges with an estimated savings of 10-30% over simple spans.[57] The Montana Highway Department also "turned definitely to continuous spans" and in 1938 extended the possibilities of the short-span arched continuous truss highway bridge with a three-span deck truss (84'-168'-84) over the Middle Fork of the Flathead River at Belton Montana. The bridge was built at an amazing cost of only $74,815 and won the AISC Class C award for 1938.[58]

The unique three-span deck/thru-arch/deck continuous truss design pioneered by FS&T was copied for years to come for major and minor highway bridges around the country where aesthetics and cantilever construction were necessary factors. As new bridge technologies and design concepts developed they were integrated into the design type to create hybrid forms of continuous arched truss bridges. The monumental 53-span Susquehanna River between Havre de Grace and Perryville, Maryland, designed by J.E. Greiner and completed in 1941, used two 3-span units identical in appearance to the Cape Cod Canal bridges, but supported by pinned Wichert rhomboid panels over the piers to make them statically determinate structures.[59] The 1949 Julien Dubuque Bridge over the Mississippi at Dubuque, Iowa established a new world's record for a continuous truss by using the deck structure in tension to tie the 845' main arch span. The tie allowed a 25% reduction in the height of the arch resulting in significant savings in material and erection costs (**Figure** 7).[60]

Engineers of the General Sullivan Bridge

The engineering consulting firm of Fay, Spofford & Thorndike was established on July 1, 1914 by Frederic H. Fay, Charles M. Spofford, and Sturgis H. Thorndike. All three men were classmates and graduates of the Massachusetts Institute of Technology civil engineering program and studied under George F. Swain. Fay and Spofford graduated together in 1893, Thorndike graduated in 1895 and they remained in contact thereafter. Fay and Thorndike worked together as engineers for the City of Boston for over fifteen years, and Thorndike taught occasional courses at MIT where Spofford was a full time professor.

Frederic Harold Fay

Frederic Harold Fay was born in Marlboro, Mass. on July 5, 1872 and died at his home in Dorchester, Mass. June 5, 1944. Following completion of his Bachelor's degree at MIT he was accepted to the school's new graduate program. In 1894 he became the first person to receive a Master of Science in Civil Engineering from MIT. Fay worked briefly for Boston Bridge Works and then in 1895 joined the engineering department of the City of Boston where he rose to the position of Engineer in Charge, Boston Bridge and Ferry Division, Department of Public Works.

In 1909 Fay authored a paper with Spofford and another city engineer, J.C. Moses, on the reconstruction of the Boylston Street Bridge over the Boston and Albany Railroad, a major undertaking for the city.[61] He resigned from the City in 1914 to join in partnership with Spofford and Thorndike. Fay took an interest in large scale planning projects and became the firm's expert in that field. Among his many projects one of the largest was the design of the $25 million Boston Army Supply base at South Boston built 1918 to 1919. He was chairman of the Boston Planning Commission from 1922 to 1939, a member of the State Planning Board, and a president of the Boston Society of Civil Engineers.[62] In 1948, to commemorate its 100-year anniversary, the society asked several of its leading members to write articles on the outstanding contributions to engineering made by former members. Spofford was asked to write about those who contributed the most to the field of structural engineering and chose three: George F. Swain (1857-1931), Joseph R. Worcester (1860-1943) and Frederick H. Fay (1872-1944).[63] Spofford pointed to the Lake Champlain Bridges (FS&T also designed the Rouses Point Bridge over the lake in 1937), his port and maritime studies and designs, and his grade crossing elimination project designs including the massive Syracuse project completed by the New York Central Railroad.[64]

Charles Milton Spofford

Charles Milton Spofford was born in Georgetown, Massachusetts on September 28, 1871 and died in Newton, Mass. July 2, 1963 at the age of 91.[65] Like Fay, Spofford also did post-graduate studies in civil engineering from 1893-1894, but it is not clear if he completed his Masters degree. He co-authored a thesis in 1893 for his B.Sc. degree entitled "An investigation into the action of elliptical car springs."[66] Spofford worked for the Phoenix Bridge Company from 1895 to 1899, but only summers from 1897-1899 when he taught in the MIT engineering program as an assistant instructor during the school year. He taught at MIT full time as an assistant professor from 1903 to 1905, then accepted a professorship in civil engineering at Polytechnic Institute of

Brooklyn from 1905 until 1909. In that year he returned to MIT to accept the position of Hayward Professor of Civil Engineering where he remained until his retirement in 1954.

Spofford published a college engineering textbook in 1911 entitled "The Theory of Structures" which became a standard and was republished in four editions, the last being in 1939.[67] He was not a prolific writer or engineering theorist however. His only other major work was his 1937 textbook *The Theory of Continuous Structures and Arches* which joined several other in an increasingly crowded field. He wrote about ten articles for journals. Useful contributions are the Boylson Bridge article he wrote with Fay, a detailed investigation of highway bridge floor types, a historical piece on Thaddeus Hyatt - an early American inventor of reinforced concrete, a method for the division of bridge costs between street railways and cities, and his report on the use of proving rings that resulted from his work on the General Sullivan Bridge.[68] His other half-dozen articles reported on the salient features of important bridge design work done by FS&T, but did not really add materially to the greater body of engineering knowledge.[69] In 1942 he chaired the American Society of Civil Engineers (ASCE) in-house sub-committee that reported on the Tacoma Narrows Bridge collapse.[70]

Sturgis Hooper Thorndike

Sturgis Hooper Thorndike was born June 11, 1868 in Beverly, Massachusetts. He received a B.A. from Harvard in 1890 and a B.Sc. in civil engineering from MIT in 1895. Following graduation he entered the employ of the City Engineer of Boston where he spent the first 18 years of his career. His work for the city involved a large amount of bridge design, and in 1906 he was made assistant engineer in charge of bridge design. He had a major role in many of the city's prominent bridges including the Longfellow Bridge over the Charles River to Cambridge. Between 1904 and 1906, he was granted a leave of absence from the City during the school terms to teach engineering courses at MIT. In 1911 he was promoted to Designing Engineer of the Bridge and Ferry Division of the Department of Public Works, but later in the year resigned the position to establish a private consulting practice. In 1914 he formed a consulting partnership with fellow MIT alums Fay and Spofford. Thorndike remained a principal of the firm until his death February 16, 1928 at the age of sixty.[71]

Howard James Williams

Howard James Williams, of Fay, Spofford & Thorndike, served as "assistant engineer in charge of detailed design" on the General Sullivan Bridge project.[72] Williams was born in Kingston, Canada in 1895, received his B.Sc. in civil engineering from Queens College, Kingston in 1917, and his M.Sc. in engineering from MIT in 1920. He worked for several firms as an engineer on hydropower developments at Niagara Falls, Quebec and Maine until 1926 when he joined FS&T as a senior engineer. He became a partner in 1947 and an officer/director of the firm in 1956. His obituary was not located but he was still with FST in 1964. In addition to his bridge design work, Williams was chiefly responsible for design work on the New Jersey Turnpike and the Port of Portland, Maine.[73]

Andrew Peter Ludberg

Andrew Peter Ludberg, was employed by the Lackawanna Steel Construction Corporation as Resident Engineer in charge of the steel superstructure on the Little Bay Bridge.[74] Ludberg was born in 1889 in Ostersund, Sweden and immigrated to the U.S. when he was four. He received a B.Sc. in civil engineering from the University of Wisconsin in 1911 and after graduation joined the engineering department of the Chicago, Milwaukee, St. Paul & Pacific Railroad. He worked for the American Bridge Company as a structural draftsman from 1913 to 1921. Between 1921 and 1927 he was associate professor of civil engineering at the University of Idaho.[75] He briefly returned to American Bridge Company, but soon accepted the position of chief draftsman the Lackawanna Steel Construction Corporation. Ludberg possessed a "remarkable skill in mathematical analysis and insight into the elastic behavior of structures, especially those of the 'higher' and indeterminate type," and it likely because of those abilities that he was assigned resident engineer on the Little Bay Bridge project.[76] On April 11, 1934, during his routine morning inspection of the steel work, Ludberg stepped on an unattached section of concrete formwork on Span 3 and fell to his death. He was the only fatality resulting from the construction of the General Sullivan Bridge.[77]

General Sullivan Bridge Stress Analysis Methods

The question has been raised regarding the significance of the mathematical methods used in the design of the General Sullivan Bridge and whether they constituted relatively new or sophisticated methods to analyze stresses in continuous structures. The analytical methods chosen were not new or sophisticated and were apparently chosen due to their familiarity, ease in checking, and suitability to be divided among a staff of calculators. Spofford's 1911 textbook was not the first to bring these methods to light, and no evidence was found that his treatment of the subject was considered exceptional by his peers.

Spofford states that the Method of Least Work was used to calculate the stresses in the continuous trusses of the bridge and explains the procedure: "A preliminary design was first made using reactions as determined by the 'Three Moment Equation; this was followed by a more accurate determination of the stresses applying the least work principle and revising the section areas accordingly."[78] There was nothing particularly novel or significant about this mathematical approach to the problem at the time, it was one of the oldest mathematical methods for solving elastic theory problems. Spofford and his "calculators" who performed the laborious and repetitive calculations used the same methods for the design of the Lake Champlain Bridge six years earlier. In discussing the Lake Champlain project, Professor Robert Abbett questioned the immense labor of using the method of least work, when better methods were available.[79] Spofford replied that he found the least work method preferable when the computations can be divided among several staff members.

The "three moment equation" originated with the French engineer Clapeyron who studied a continuous beam with three supports. The load on the center support depends on the length of the beam, but also on its elasticity. Clapeyron discovered a mathematical relationship between the bending moments (three) at each support based on the loads on the beam between each support. He published his theorem in 1857 and it has since been known as Clapeyron's Theorem of Three Moments.[80] The reactions on continuous girders can be accurately determined using the theorem if the entire beam is of constant section and material (constant moments of inertia and modulus of elasticity), if not then the method requires a series of repeated calculations in which the reactions are approximated and results adjusted to obtain the desired accuracy.[81]

The Italian engineer Alberto Castigliano (1847-1884) presented the method of least work theory in his book "Theorie de l'equilibre des systemes elastiques et ses applications" published in Turin in 1879. The first to explain Castigliano's theories in English was MIT (later Harvard) professor George F. Swain in 1883.[82] It was not until 1919 that Castigliano's book was translated in full into English by British engineer E. C. Andrews under the title *Stresses in Elastic Structures*.[83]

The first comprehensive presentation of the method of least work in the U.S. appears to be an 1891 article by William Cain who gave this introduction to the subject:

> The method is found to be of very general application to all structures in which the laws of elasticity have to be considered in finding the stresses; as in every kind of beam or arch, trusses of any shape with superfluous members and all systems where there is a continuity in the members or where there is not free play at the joints, as in nearly all roof or bridge trusses. It further offers an exact method by which we can ascertain the limit of error made in our ordinary approximate computations (which apply only to articulated systems, free to move at all the joints), and thus exposes some of the unknown errors which are usually included in our "factor of safety," though it has more appropriately been termed our "factor of ignorance".[84]

Probably the best simple introduction to the principle and application of the method of least work is that given by British engineer, Harold M. Martin in 1895:

> Every metallic or wooden structure is elastic, and constitutes a spring. If a spring is loaded by a weight, it elongates, and a certain amount of work is done in this elongation. This work is stored in the spring in the form of potential energy, and can be reconverted into mechanical work, as is commonly done in clocks and watches. The stiffer the spring the less it is deformed by a given weight, and hence less work is stored in a stiff spring loaded with a 1-lb. weight than in a light one loaded by the same weight. Thus if 1 ton is hung from a steel bar of 2 square inches in section, less work is done in deforming the bar than if it was hung on a steel bar of the same length and of 1 square inch section. If a weight lies on a platform supported by four legs of elastic material, work will be done in deforming the platform and compressing the legs.
>
> If there had been only three legs, the ordinary principles of statics would suffice to determine the weight taken by each leg, which is then quite independent of the comparative stiffness of the legs and the platform. When, however, we have more than three legs, these statical principles no longer suffice, and to determine how much of the weight is carried by each leg it is necessary to introduce other considerations. The one great principle to which such problems can be reduced is known in dynamics as that of

least action, and in such problems as we have before us as that of "least work." That is to say that the work stored in an elastic system in stable equilibrium is always the smallest possible.[85]

Martin goes on to describe in simple mathematical terms how to solve for the load carried by each leg with a given weight located at a certain place on the table, and then proceeds into analyzing increasingly complicated frames.

Through the 1890s up to the mid-1930s, a great number of important articles and textbooks were published on the subject of statically indeterminate structures, several of which are discussed below. For a broader review of the body of work on the subject, the reader is referred to the endnote for two excellent historical summaries on the subject.[86]

A paper given in 1899 by Frank E. Cilley discussed the futility of hoping to analyze indeterminate structures with an exactness and provoked contrary discussion by such majors as Lindenthal and Swiss professor C.W. Ritter. Lindenthal called the paper "a contribution to the old controversy as to whether or not statically determinate structures are superior to statically indeterminate ones, and is a scholarly attempt on the affirmative side of the equation."[87] Cilley's paper was a brilliant thesis that argued with sophisticated mathematical reasoning that a determinate structure can and should supplant an indeterminate one in every case, and that structural redundancy therefore equals structural waste. This work had a lasting effect in dividing American engineers into two camps, and as noted in the historical section above, it was not until Lindenthal and several other leaders built major continuous trusses, and new minds reasoned their economic validity, that the merit of indeterminate bridges became generally recognized.[88]

In 1905 Professor Isami Hiroi of Tokyo Imperial University wrote the first textbook in English (published in the U.S by Van Nostrand) on the use of the method of least work to solve for secondary stresses in bridge trusses.[89] Carl Grimm devoted a chapter to using the method of least work in his 1908 book *Secondary Stresses in Bridge Trusses*, as well as chapters on the four other leading methods for solving secondary stresses: Manderla method, Muller-Breslau method, Ritter method, and Maxwell-Mohr method.[90]

In 1911, the two leading college structural engineering textbook authors - Johnson, Bryan & Turneaure and Merriman & Jacoby - came out with new editions of their multi-volume treatises that included sections on the complete application of method of least work.[91] Two more textbooks, C.M. Spofford's *Theory of Structures* (1911) and *Theory of Framed Structures* (1922) by C.A. Ellis both contained sections on indeterminate structures and the method of least work.

In 1926, John I. Parcel and George A. Maney published the *An Elementary Treatise on Statically Indeterminate Stresses*.[92] This became arguably the leading text on the subject for decades, coming out in three editions until it was complete revised with a new title and coauthor in 1955 as *Analysis of Statically Indeterminate Structures*.[93] Parcel was professor of structural engineering at the University of Minnesota and later a partner in the firm of Sverdrup & Parcel. He called Johnson, Bryan and Turneaure's 1911 *Modern Framed Structures* "the best and most comprehensive treatment of statically indeterminate stresses in the English language."[94]

The first major American contribution to the analysis of statically indeterminate structures was made by Hardy Cross in 1930 when he described a new method for analyzing building frames that became known as the moment distribution method. When published in the ASCE *Transactions* in 1932, it was followed by 146 pages of discussion from 38 commentators, possibly a record. "Cross was immediately hailed as the man who had solved one of the knottiest problems in structural analysis."[95] His method was later called "probably the most notable advance in structural analysis during the twentieth century."[96] The Cross method was readily applied to solving secondary stresses in trusses, as demonstrated by Professor F.P. Witmer, head of the engineering department at the University of Pennsylvania, who applied it to the same 150' Warren truss example as was used by von Abo in his landmark 1926 paper. Witmer completed the analysis in only six hours, and claimed that the method "will prove to be the simplest and most expeditious method yet advanced for this purpose.[97] Had FS&T used the Cross method to solve the stresses of the General Sullivan Bridge, that would have been a first. Instead, the first to apply the moment distribution method to a continuous truss appears to be Truman P. Young, a structural engineer from Ohio, who designed a 3-span continuous arched truss and published his procedure in 1936.[98]

NOTES

[1] Robert W. Abbett, "Discussion on Lake Champlain Bridge," *Transactions of the American Society of Civil Engineers* 98 (1933): 654.

[2] Mansfield Merriman and Henry S. Jacoby, *A Textbook on Roof and Bridges, Part IV, Higher Structures* (New York: John Wiley & Sons 1912), p. 32. For a detailed description of the Lachine Bridge see *Engineering News*, October 1, 8, 15, 1887.

[3] J.A.L. Waddell, *Bridge Engineering* (New York: John Wiley and Sons 1916), p. 25.

[4] American Society Of Civil Engineers, *A Biographical Dictionary of American Civil Engineers* (New York: American Society Of Civil Engineers 1972), p. 81. For an in-depth biography of Lindenthal see Henry Petroski, *Engineers of Dreams* (New York: Alfred A. Knoph 1995).

[5] "Bridges," *Encyclopedia Britannica*, vol. 4 (Chicago: Encyclopedia Britannica, Inc 1954), p. 126.

[6] "Long Span Continuous-Truss Bridge over the Ohio," *Engineering News* (July 8, 1915): 64-66; "Will Soon Complete Sciotoville Continuous Bridge" *Engineering News* (May 17, 1917): 343-344; Gustav Lindenthal, "The Continuous Truss Bridge Over the Ohio River at Sciotoville, Ohio, of the Chesapeake and Ohio Northern Railway," *Transactions of the American Society of Civil Engineers* 35 (1922): 910-975.

[7] Clyde B. Pyle, "Problems and General Methods of Erecting the Sciotoville Bridge, *Engineering News-Record* (January 10,1918): 62-68; (January 31, 1918): 219-227; (December 26, 1918): 1182-1186.

[8] "Continuous Trusses of Silicon Steel Feature New Allegheny River Bridge," *Engineering News-Record* (May 2, 1918): 848-856.

[9] "Nelson River Crossed by Hudson Bay Railway on Large Continuous-Truss Bridge," *Engineering News-Record* (August 29, 1918): 388-393.

[10] In 1919 British engineer Ewart C. Andrews published the complete English translation of Castigliano's 1879 "Theorie de l'equilibre des systemes elastiques et ses applications" under the title *Stresses in Elastic Structures* (London: Scott & Greenwood 1919); See also H. M. Westergaard, "Buckling of Elastic Structures," *Transactions of the American Society of Civil Engineers* 85 (1922): 576+; O. H. Ammann, "Secondary Stresses in Steel Riveted Bridges," *Engineering News-Record* (October 23, 1924): 666-668; Cecil Vivian von Abo, "Secondary Stresses in Bridges," *Transactions of the American Society of Civil Engineers* 89 (1926):1-193; John I. Parcel and George A. Maney, *An Elementary Treatise on Statically Indeterminate Stresses* (New York: John Wiley & Sons 1926); L. H. Nishkian and D. B. Steinman, "Moments in Restrained and Continuous Beams by the Method of Conjugate Points," *Transactions of the American Society of Civil Engineers* 90 (1927):1-143; Hardy Cross, Virtual Work: A Restatement," *Transactions of the American Society of Civil Engineers* 90 (1927):610-626. Two textbooks that entered the structural analysis field in the mid-1930's should be noted: *The Analysis of Engineering Structures* by A.J.S. Pippard and J.F. Baker in 1936, and *The Theory of Continuous Structures and Arches* by Charles M. Spofford in 1937.

[11] Gustav Lindenthal, "The Continuous Truss Bridge Over the Ohio River at Sciotoville, Ohio, of the Chesapeake and Ohio Northern Railway," *Transactions of the American Society of Civil Engineers* 35 (1922): 910-975.

[12] C.A.P. Turner, "Discussion on Sciotoville Bridge over the Ohio River," *Transactions of the American Society of Civil Engineers* 35 (1922): 954, 961.

[13] Lindenthal, "The Continuous Truss Bridge Over the Ohio River at Sciotoville, Ohio, of the Chesapeake and Ohio Northern Railway," pp. 971-975.

[14] Daniel B. Steinman, "Discussion on Sciotoville Bridge over the Ohio River," *Transactions of the American Society of Civil Engineers* 35 (1922): 964.

[15] Cecil Vivian von Abo, "Secondary Stresses in Bridges," *Transactions of the American Society of Civil Engineers* 89 (1926): 1-193.

[16] Gustav Lindenthal, "Bridges With Continuous Girders," *Civil Engineering* (July 1932): 424.

[17] Lindenthal, "Bridges With Continuous Girders," p. 423. Note: It could not be conclusively determined from a review of the literature who built the first continuous truss highway bridge in the U.S., but it appears to have been Lindenthal. In 1932 Lindenthal wrote an article entitled "Bridges with Continuous Girders" in which he reviewed the American practice over the previous fifty years. Lindenthal studied various designs for continuous truss bridges in 1883 and in that year built a variation of the type using the "funicular principle" with counterweights at the piers to balance the stresses in the trusses. The Herr's Island Bridge carried a highway over the Allegheny River near Pittsburgh with three thru-spans of 200'-300'-200'. In 1890 he built another bridge on the same principle to carry highway and streetcar traffic over the Monongahela River at McKeesport. Lindenthal abandoned the funicular principle and it was not until the late 1930s that the principle was incorporated into the patented Wichert Truss system to combine the advantages of continuity with a statically determinate design.

[18] "Steel Arch Closure Effected with Aid of Temperature Changes," *Engineering News-Record* (November 11, 1926): 796-797.

[19] Robert W. Abbett, "Discussion on Lake Champlain Bridge," *Transactions of the American Society of Civil Engineers* 98 (1933): 654.

[20] Charles M. Spofford, "Lake Champlain Bridge," *Transactions of the American Society of Civil Engineers* 98 (1933): 632.

[21] Ibid., p. 633.

[22] Ibid.

[23] Ibid., p. 624.

[24] "Bensalem Avenue Bridge, An Essay in Ornamentation," *Engineering News-Record* (September 16, 1920): 559-561.

[25] "What is Art?" *Engineering News-Record* (September 16, 1920): 531; Rudolph Hering, "What is Art?" *Engineering News-Record* (September 30, 1920): 670; N.H. Holmes, "What is Art? A Defense of the Architect," *Engineering News-Record* (October 21, 1920): 810; George E. Dorman, "What is Art? The Worm Turns," *Engineering News-Record* (November 18, 1920): 1006; F. H. Frankland, "What is Art?" *Engineering News-Record* (December 2, 1920): 1105

[26] Gustav Lindenthal, "Some Aspects of Bridge Architecture," *Scientific American* (November 1921): 22.

[27] Ibid.

[28] "Annual Bridge Awards by Institute of Steel Construction," *Engineering news-Record* (August 7, 1930): 225.

[29] F. H. Frankland, "Trend in Modern Steel Bridge Design," *Canadian Engineer* 57 (October 1, 1929): 170.

[30] "Continuous Truss Highway Bridge Over Missouri River," *Engineering News-Record* (January 17,1929): 100-102.

[31] I.L. Pesses, "Silicon Steel Used Liberally in 1257-ft Continuous Truss Bridge," *Engineering News-Record* (October 9, 1930): 572-575.

[32] "Awards made for Most Beautiful Bridges of 1930," *Engineering News-Record* (July 2,1931): 30.

[33] "Three Bridges Get Steel Institute Award," *Engineering News-Record* (July 1,1933): 723. Note: For a full description of the French King Bridge see: Albert E. Kleinert, "Design and Construction of the French King Bridge on the Mohawk Trail Route Across the Connecticut River, Massachusetts," *Journal of the Boston Society of Civil Engineers* (June 1933): 117-135.

[34] Lindenthal, "Bridges With Continuous Girders," pp. 421-424.

[35] Ibid., p. 423.

[36] Charles M. Spofford, "Little Bay and Bellamy River Bridges," *Journal of the Boston Society of Civil Engineers* (January 1935): 3-4.

[37] "High-Level Bridge Link in the Dover-Portsmouth Road," *Engineering News-Record,* (September 27,1934): 387.

[38] Spofford, "Little Bay and Bellamy River Bridges," p. 6.

[39] Spofford, "Lake Champlain Bridge," p. 647.

[40] Spofford, "Little Bay and Bellamy River Bridges," p. 6-7; "High-Level Bridge Link in the Dover-Portsmouth Road," pp. 388-389.

[41] Spofford, "Little Bay and Bellamy River Bridges," 12, 14.

[42] C. M. Spofford and C. H. Gibbons, "Weighing Bridge Reactions With Proving Rings," *Engineering News-Record* (March 28, 1935): 446-449.

[43] Ibid, p. 446.

[44] Ibid.

[45] Spofford, "Little Bay and Bellamy River Bridges," p. 14.

[46] Spofford and Gibbons, "Weighing Bridge Reactions With Proving Rings," p. 447.

[47] "Three New Bridges for Cape Cod Canal," *Engineering News-Record,* (January 25,1934): 107-109; "First of Cape Cod Bridges Erected," *Engineering News-Record* (November 8, 1934): 607; "Institute Awards Prizes to 2 Bridges," *New York Times* (June 7, 1935):11.

[48] The Most Beautiful Bridges Built Last Year," *Engineering News-Record* (June 12, 1935): 857; "Awards for Beautiful Bridges," *Engineering News-Record* (July 2, 1936): 28.

[49] I.L. Pesses, "Silicon Steel Used Liberally in 1257-ft Continuous Truss Bridge," *Engineering News-Record* (October 9, 1930): 572-575.

[50] Charles M. Spofford, "Cape Cod Canal Bridges," *The Military Engineer* 28 (May-June 1936): 168.

[51] L.J. Sverdrup, "Continuous Truss Highway bridge over Missouri River," *Engineering News-Record* (January 17, 1929): 100-102; Pesses, "Silicon Steel Used Liberally in 1257-ft Continuous Truss Bridge," pp. 572-575.

[52] Albin L. Gemeny, "Bridge Engineering in 1937," *Engineering News-Record* (February 10, 1938): 233-234.

[53] "Awards for Beautiful Bridges," *Engineering News-Record* (July 2, 1936): 28.

[54] "Building Bridge for Future River Channel," *Engineering News-Record* (May 23, 1935): 727-732.

[55] J.I. Parcel, "Long Continuous Truss Bridge Spans Mississippi River," *Engineering News-Record* (September 10, 1936): 362-364.

[56] "Building Davenport Bridge Across Mississippi," *Engineering News-Record* (December 19, 1935): 837-841.

[57] G.W. Lamb, "Continuous Spans Favored for Kansas Highways, *Engineering News-Record* (November 21, 1935): 702-706.

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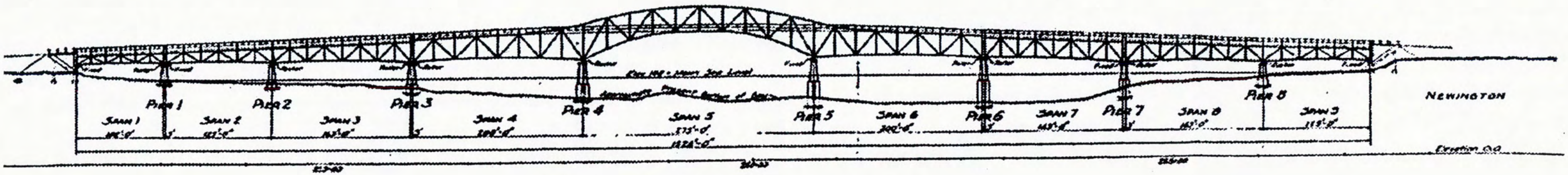

ELEVATION
LITTLE BAY BRIDGE

vation Little Bay Bridge (NHDOT)