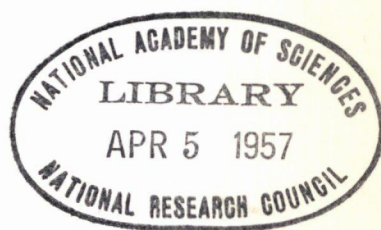# HIGHWAY RESEARCH BOARD
Bulletin 144

Some Cost Data on Prestressed Concrete Bridges

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Some Cost Data on Prestressed Concrete Bridges

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Prestressed Concrete Bridge Costs

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● THE original intention in preparing this paper on "Prestressed Concrete Bridge Costs" was to detail fully the cost of work done in Massachusetts on this type of construction since the Department's first venture into this field in August of 1951, but the pressure of emergency flood replacement work, in addition to an accelerated highway program, has prevented a complete analysis and breakdown of these costs.

This paper, however, enumerates the post-tensioned projects, giving a brief description, including their square-foot costs, and covers the more recent pretensioned work on flood bridges. These earlier projects are summarized in Table 1.

The first contract, in 1951, was for a railroad overpass bridge in Danvers. It is a 27-ft span structure and contains 47 inverted T-type beams. The beams are 14 in. deep and have a width of flange of 12 in. The bottom flanges are butted in place on the bridge seats, and the areas between and over the flanges are filled with concrete, making in effect a composite concrete slab. This is the only post-tensioned structure built by the Department in which the strands were not grouted in place. The beams were fabricated under a separate contract and the cost of the deck was $7.50 per sq ft.

All six of the other post-tensioned structures have beams of an I-shape, spaced generally about 4.5 ft on centers, with a poured-in-place slab on top of the beams. The spans of these bridges vary from 58 ft to 67 ft.

The beams for the four bridges in Newbury and Newburyport on the Newburyport Turnpike were furnished under a separate contract; those in the Wenham and Bridgewater projects were included in the general contract.

All the beams for these bridges, except those for the Scotland Road Bridge, have a depth of 36 in., a bottom flange width of 24 in., a top flange width of 20 in., and a web thickness of 6 in. The Scotland Road Bridge has a depth of 3 ft 8 in.; otherwise, the dimensions are the same.

The cost of the deck of the Wenham Bridge was $13.75 per sq ft; that of the Bridgewater Bridge, $11.10; the Scotland Road Bridge, $10.00; the Hale Street Bridge, $9.60; the Storey Avenue Bridge, $8.50; and that of the Pine Hill Road Bridge, $10.60.

Earlier designs were very conservative and did not take full advantage of high strength concrete. If the same structures were designed today, a 15 percent reduction in cost could be effected.

All of the post-tensioned beams were manufactured by one company, and all, except those on the Danvers project, were manufactured in an outdoor yard and under adverse weather conditions.

The storm of August 1955, whose axis coincided approximately with the Massachusetts - Connecticut state line, destroyed or badly damaged about 220 small bridges in 80 cities and towns in Massachusetts.

The estimated cost of replacement of these structures and their immediate approaches is about $9,000,000. The work of this rehabilitation program will be financed by a flood bond issue with reimbursement to the state by the Bureau of Public Roads on federal-aid projects and by the Army Engineers to the extent of the estimated cost of temporary bridges if their construction is not required.

The damage was confined primarily to bridges on small streams. Many of these were destroyed because of the failure of old and inadequate dams to withstand a flash flood of such magnitude.

In order to speed replacement, 17 boring crews were put into the field on September 1, and, shortly thereafter, 22 consulting engineers were engaged to prepare plans for the new bridges and their approaches. The devastated portion of the state was divided into 22 geographical areas, made up generally of a group of adjacent towns, and a consultant was assigned to each area.

A cursory survey of the damaged areas showed that by far the greater percentage of the bridges to be replaced would have spans under 40 ft, and a study indicated that rectangular pretensioned units would be particularly suited for this span range.

Municipality	Location	Date Built	Span	Cost per sq ft
Danvers	Endicott Street over B & M. R. R.	1951	27'	$ 7 50
Wenham	Grapevine Road over Route 128	1952	2 at 60'	13 75
Bridgewater	Pleasant Street over Fall River Expressway	1953	2 at 67'	11 10
Newbury	Newburyport Turnpike over Scotland Road	1953	65'	10 00
Newbury	Hale Street over Newburyport Turnpike	1953	2 at 64'	9 60
Newburyport	Storey Avenue over Newburyport Turnpike	1953	2 at 58'	8 50
Newburyport	Pine Hill Road over Newburyport Turnpike	1953	2 at 59'	10 60

It was decided to replace all the structures having spans of from 20 to 40 ft with this type of superstructure, the Department preparing the plans and advertising for separate bids for the furnishing of the units. At the time of this decision, the exact number and locations of the bridges in this span range were not known, but it was planned to advertise for the construction of about fifty bridge decks.

To keep the form requirements and the costs to a minimum, two depths of beams were selected, 17 in. for the 20- to 30-ft span beams and 21 in. for the 30- to 40-ft span lengths.

The proportion between the two depths was an arbitrary one based on meager information and was at the ratio of about three for the 17-in. depth beam and one for the 21-in. depth beam.

The majority of these bridges are located on secondary roads where the general roadway design width is either 26 ft or 30 ft. Allowing for a 12-in. width of curb, a 4-ft width of beam satisfied the requirements, both for roadways and for sidewalks. Consequently, this width was adopted, reducing to a minimum the number of units necessary for each bridge.

Two basic sections were detailed for each depth of beam: Type A, or roadway beam, and Type B, or curb beam. A third basic beam section, 17 in. deep, was detailed for the sidewalks for all spans.

All 17-in. depth beams contain three $8\frac{1}{2}$-in. diameter economy holes, and all 21-in. depth beams contain three $10\frac{1}{2}$-in. holes. These holes are blocked at the ends and at the center to allow for the insertion of pipe sleeves, placed parallel to the abutments, through which $\frac{7}{8}$-in. diameter lateral rods are to be threaded.

Since the majority of these beams are to be erected in the dead of winter when the grouting can not be done, a 1-in. space is to be left between the beams and for the full depth, so that water will not be pocketed between the beams and, in freezing, damage them.

Where the beams are erected before spring, a gravel surface will be placed on the deck and the bridge opened to limited traffic. When the weather is suitable, the gravel will be removed, the space grouted, membrane water-proofing applied, and a bituminous concrete surface laid.

The only variable of any consequence in the beams is the amount of prestressing steel required. Because of the variation of spans from 20 to 40 ft and loadings from H15 to H20 S16 with a modified military provision, a table of $\frac{3}{8}$-in. diameter strand requirements was prepared for span lengths increasing by 5-ft increments, under four

TABLE 2

STRANDS REQUIRED FOR RECTANGULAR PRESTRESSED CONCRETE BEAMS

Type of Beam	Loading	17" Depth No. of $\frac{3}{8}$" Strands		21" Depth No. of $\frac{3}{8}$" Strands	
		Spans 20' to 25' incl	Over 25' to 30' incl	Over 30' to 35' incl	Over 35' to 40' incl
A Standard and B Curb	H-15	5 top, 22 bottom	6 top, 28 bottom	6 top, 30 bottom	8 top, 36 bottom
	H-20	5 top, 26 bottom	7 top, 32 bottom	8 top, 34 bottom	10 top, 44 bottom
	H-20-S16	6 top, 26 bottom	8 top, 36 bottom	8 top, 40 bottom	11 top, 50 bottom
	H-20-S16(M)	6 top, 30 bottom	8 top, 40 bottom	8 top, 40 bottom	11 top, 50 bottom
C Sidewalk	Sidewalk	All spans - 17" Depth - 6 top, 26 bottom. All $\frac{3}{8}$" strands.			

H-20-S16(M) = Modified for military loading.

December 15, 1955 - Revision of Number of Strands in Type B Curb Beams
Where there are more than five $\frac{3}{8}$" strands at top of slab, move two strands to top of curb and add one strand, making three strands at top of curb.
Where there are only five $\frac{3}{8}$" strands at top of slab, move one strand to top of curb and add one strand, making two strands at top of curb.

SECONDARY ROAD FENCE
6' POST SPACING
TYPE C FENCE
(MODIFIED)

MAJOR ROAD FENCE
6' POST SPACING
TYPE A FENCE
(MODIFIED)

FILL WITH GROUT

WORKING LINE

• D E T A I L •

WOOD RAILS

26'-0" OR 30'-0" ROADWAY

BITUMINOUS CONCRETE PAVEMENT, 2½" AT CURB LINE; 4' AT CENTERLINE
3 PLY MEMBRANE WATERPROOFING

VARIES, 17" & 21"

4'-0"   4'-0"   4'-0"
TYPE B BEAM   TYPE A BEAM

WORKING LINE

¾" BARS AT ½ DEPTH OF
BEAM IN 1¼" SLEEVES
(SEE PLAN)
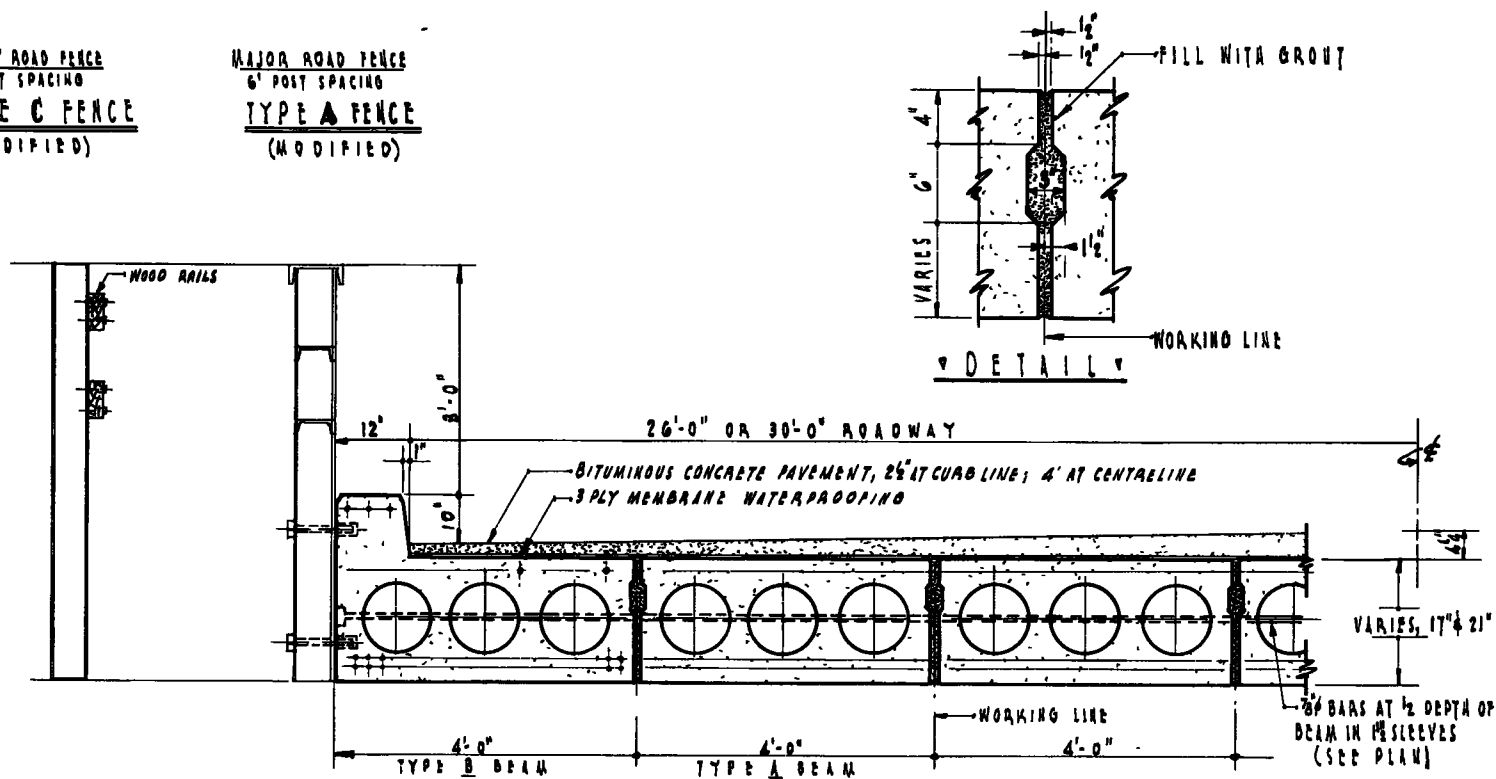
Figure 1. Partial cross-section, prestressed concrete deck.

6' POST SPACING

TYPE B FENCE

(MODIFIED)
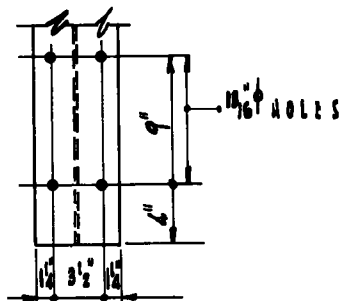
▾ELEVATION OF POSTS FOR SIDEWALKS▾

$1\frac{3}{16}"\phi$ HOLES

6"

6"

$1\frac{1}{2}"$ $3\frac{1}{2}"$ $1\frac{1}{2}"$

FILL WITH GROUT

VARIES   6'   4'

3"

$1\frac{1}{2}"$

WORKING LINE

▾DETAIL▾

3'-2"

17"

FILL WITH CAULKING COMPOUND

12"

1"

10"

26'-0" OR 30'-0" ROADWAY

BITUMINOUS CONCRETE PAVEMENT, $2\frac{1}{2}"$ AT CURB LINE; 4" AT CENTERLINE

3 PLY MEMBRANE WATERPROOFING

VARIES, 17" & 21"

$\frac{7}{8}"\phi$ BARS AT $\frac{1}{2}$ DEPTH OF BEAM, IN $1\frac{1}{2}"\phi$ SLEEVES (SEE PLAN)

4'-0"

TYPE C BEAM

4'-0"

TYPE B BEAM

4'-0"

TYPE A BEAM

WORKING LINE
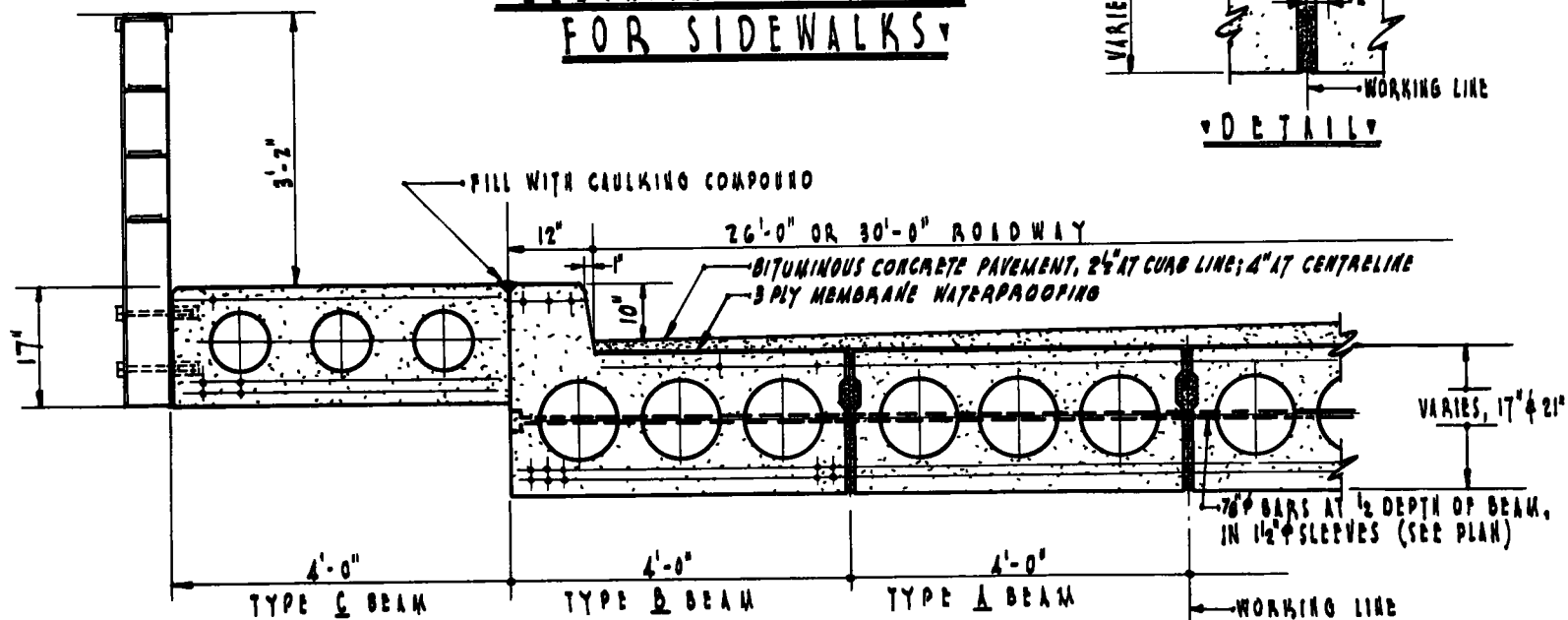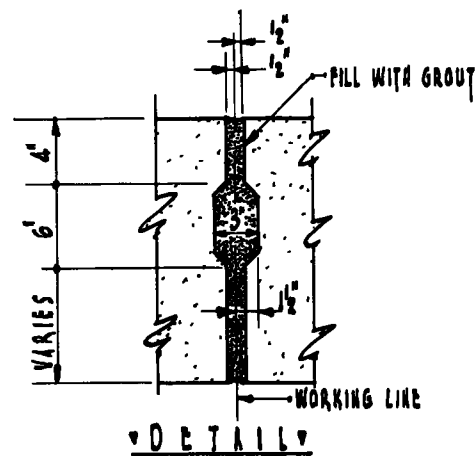
Figure 2. Partial cross-section, prestressed concrete deck with sidewalk.

design loadings, for the two depths of beams, and for the sidewalk beams. Thus, although the size of beams is limited to two depths, the number of strands in a 17-in. roadway beam varies from 27 to 48, and those in the 21-in. beams vary from 36 to 61. The sidewalk beam contains 32 strands.

The top strands in the curb beams were specified as 2 in. from the top of the slab,
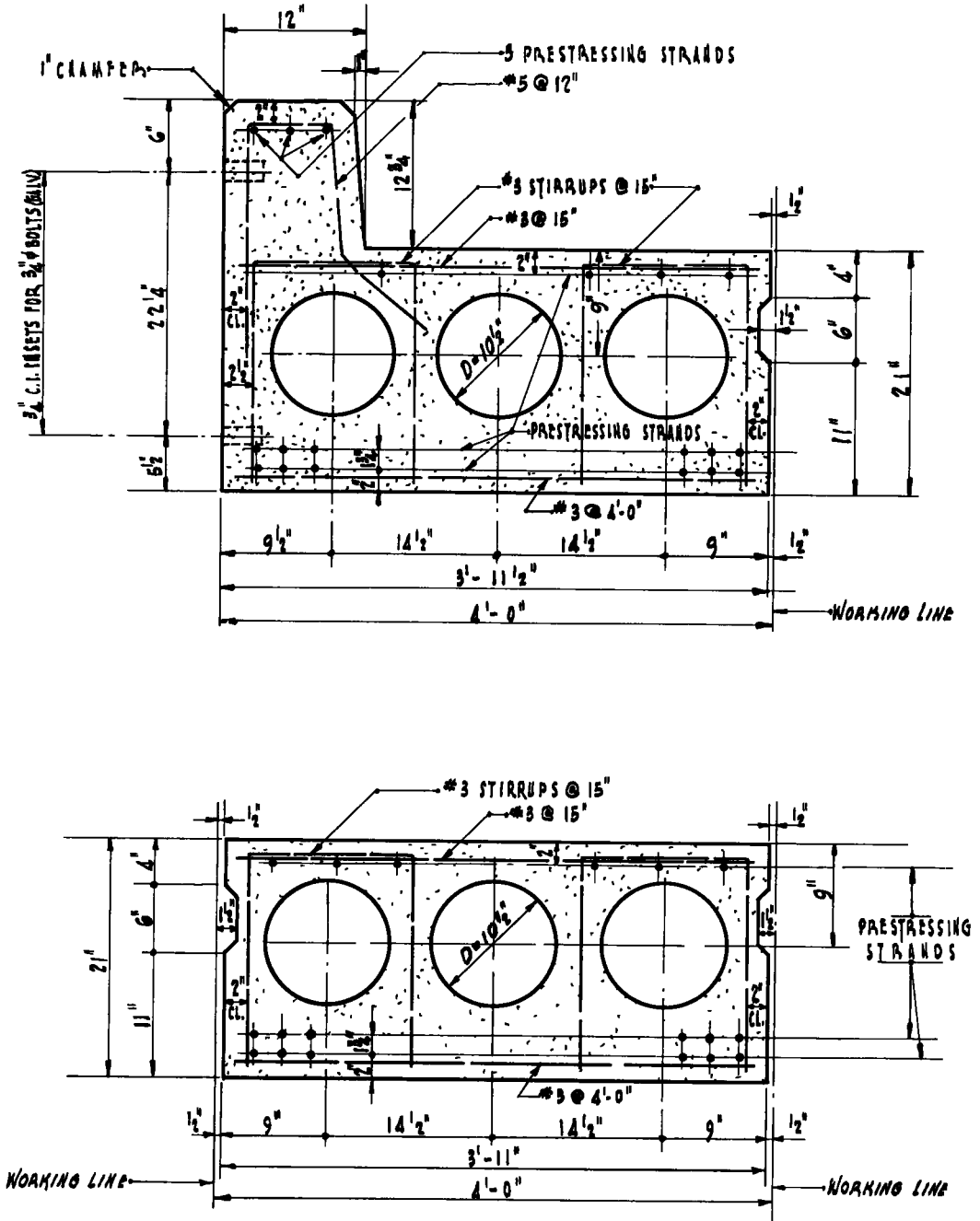
Figure 3. Type A (lower) and Type B (upper) beams, 30-ft to 40-ft span.

6

but tension in the top of the monolithically poured curb section requires the moving of some strands to the top of the curb and the addition of another strand.

A proposal was prepared containing 5 items for the furnishing of beams for about 50 bridges, and bids were received on October 11. This proposal called for payment by the lineal foot for Type A and Type B beams for each depth and contained a separate item for prestressing strands, with payment by the pound. Because the actual delivery sites were still not known for all bridges, the prices quoted were f. o. b. Worcester.
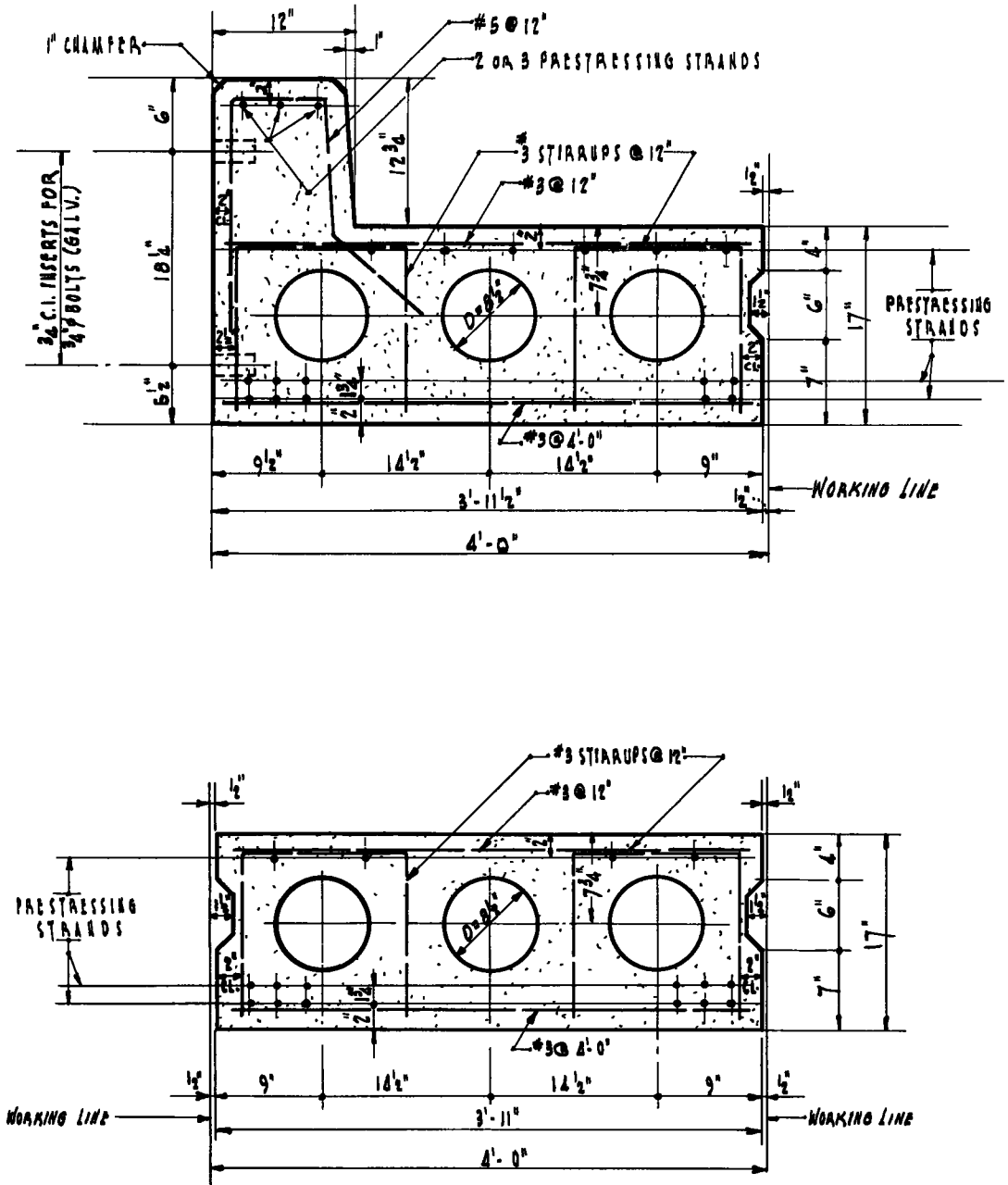
Figure 4. Type A (lower) and Type B (upper) beams, 20-ft to 30-ft span, inclusive.
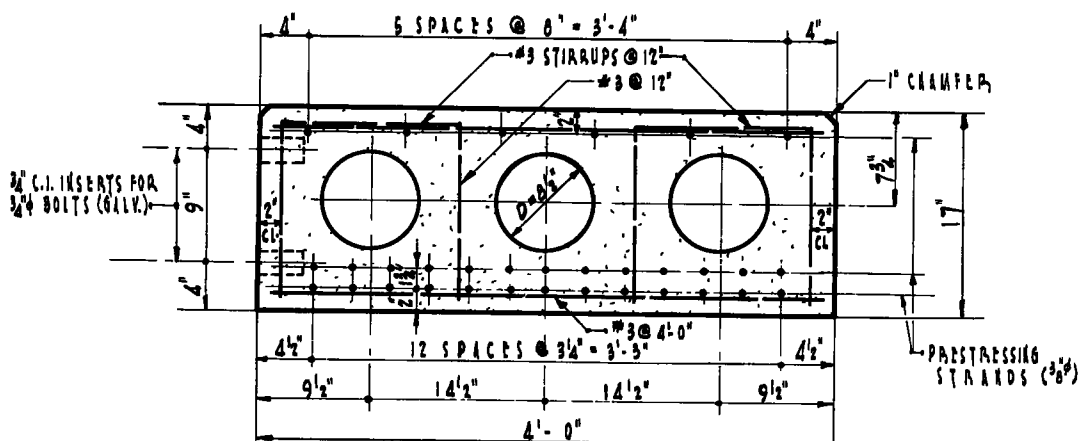
Figure 5. Type C beam, sidewalk, 20-ft to 40-ft spans.

By the time bids were opened, it was apparent that at least 30 more bridges in the selected span range could be constructed of prestressed concrete, and bids were received on November 1 for these additional beams.

There were 5 bidders on the first contract and 4 on the second. The low bid on the first contract was $185,000; the low bid on the second, $102,000.

The average detailed costs of the low bids, together with the average erection cost on bids taken to date, are shown in Table 3. These data indicate that the costs under the second contract are approximately 6 percent below the first, but that both are very economical.

The average cost per square foot of deck complete in place for spans 20 to 30 ft in length under Contract No. 1 is $5.77, and under Contract No. 2 is $5.41. For spans from 30 to 40 ft the cost is $6.37 under Contract No. 1 and $5.98 under Contract No. 2. Approximately 65 percent of the cost is in the manufacture and delivery to Worcester, and 35 percent is in the transportation from Worcester and erection on the bridge seats.

Because of the geographical location of both the plants and because of transportation arrangements between the general contractors and the suppliers, deliveries will probably be made direct to the bridge sites, and the transportation charges will be covered in the manufacturer's bid. Therefore, the general contractor's bid can be considered primarily for erection, grouting, and for the placing of the lateral ties. On the average, about 10 percent of the total cost is for the prestressing strands.

An analysis of the bid of $0.24 per pound for the strands indicates a figure of $0.44

TABLE 3

AVERAGE COSTS OF 1955 FLOOD BRIDGES WITH PRETENSIONED PRESTRESSED CONCRETE DECKS

Spans	Size of Beams	Type of Beams	Contract No. 1, 50 Bridges sq ft costs				Contract No. 2, 30 Bridges sq ft costs			
			Beams Furnished	Strands	Erection	Total	Beams Furnished	Strands	Erection	Total
20'-30'	4' x 17"	Roadway and sidewalk	3.09	$0.58	$1.87	$5.54	3.02	$0.52	$1.87	$5.41
	4' x 17"	Curb	3.92	0.58	1.87	6.37	3.02	0.52	1.87	5.41
30'-40'	4' x 21"	Roadway	3.32	0.77	2.04	6.13	3.25	0.69	2.04	5.98
	4' x 21"	Curb	4.18	0.77	2.04	6.99	3.25	0.69	2.04	5.98

Note: Costs exclusive of fences and surfacing.

AVERAGE COST PER SQUARE FOOT OF DECK

Spans	Contract 1	Contract 2
20'-30'	$5.77	$5.41
30'-40'	$6.37	5.98

SECTION A-A

FILL 1½"∅ SLEEVE WITH GROUT AT FIXED END, AND WITH BITUMEN AT EXPANSION END

FINISH BRIDGE SEATS PARALLEL TO PROFILE GRADE

6"

12"

17" OR 21"

3 LAYERS OF TARPAPER

7/8"∅ ANCHOR

DETAIL OF APPROACH SLAB
(IF REQUIRED)

SLOPE

3"

15" FOR SPANS, 20'-30' INCLUSIVE
18" FOR SPANS, 30'-40'

7/8"∅ BARS PLACED IN 1½"∅ SLEEVES. BARS TO BE THREADED, BOTH ENDS, AND FITTED WITH NUTS AND WASHERS.

15"

18"

15"

¢ OF ANCHORS

FACE OF ABUTMENT

¢ OF BAR & SLEEVE LOCATED AT ½ DEPTH OF BEAM

8½" O.D. TUBE FOR 17" BEAM
10½" O.D. TUBE FOR 21" BEAM

CENTERLINE OF BRIDGE

¢ OF BAR & SLEEVE LOCATED AT ½ DEPTH OF BEAM

4'-0"
BEAM "A"

4'-0"
BEAM "B"

9"

FACE OF CURB

SPAN LENGTH FROM ¢ TO ¢ OF ANCHORS
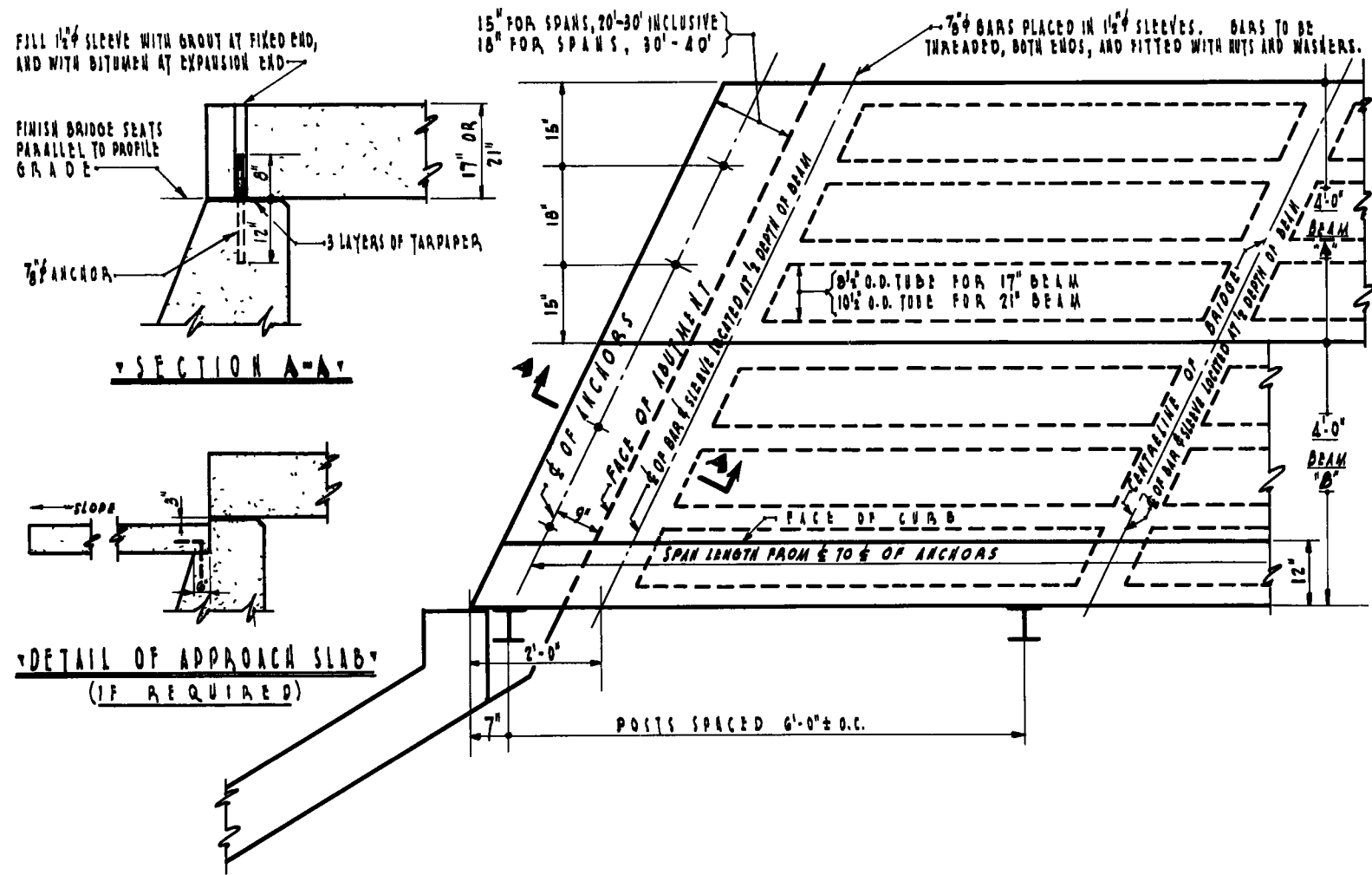
12"

2'-0"

7"

POSTS SPACED 6'-0"± O.C.

Figure 6. Plan of prestressed concrete deck.

per sq ft for a 17-in. depth beam for an H15 loading and for a 20-ft span, and a cost of
$0. 78 per sq ft for the same depth beam on a 30-ft span and an H20 S16 loading. For
similar loadings and for the minimum and maximum spans of the 21-in. depth beam,
the cost varies from $0. 59 to $1. 00 per sq ft.

Comparative Costs of Prestressed and Conventional Construction in Trestle Spans of Florida Bridges

W. E. DEAN, Assistant State Highway Engineer
State Road Department of Florida

● THE low terrain of Florida requires scores of exceptionally long bridges because of its flat slopes, broad flood plains of inland rivers, and the many wide tidal·bays and sounds separating the mainland from the highly developed beaches. Construction of new structures and replacement of old ones is a continuing procedure. Many of these bridges have over-all lengths more appropriately expressed in miles than in linear feet, but most of them are essentially very simple structures. Water depths and foundation conditions are such that, generally, adequate support for light spans can be provided by bents of friction or point bearing piles. This has resulted in many short trestle spans. The Florida bridge of great length is usually a series of dozens of identical, short, simply-supported trestle units.

Simplification and economical detailing of trestle construction is under constant study in the Florida road department. Any possibility resulting in cost savings in simple bridge building is worth considering as a small saving on a single span if applied to a large number of spans amounts to an important sum. For approximately four years, prestressed concrete has repeatedly resulted in substantial economies in the longer bridges with many identical spans and, lately, in the shorter structures.

Until recently, standard trestle spans up to about 45 ft in length, constructed near the coast with exposures to salt-laden spray and atmosphere, have usually been of reinforced concrete T-beam type. Composite I-beam concrete-deck spans were standard for longer spans and for less critical exposures on inland bridges. Spans with prestressed members are currently being used as substitutes for both of these conventional types. All prestressed construction to data has been composite and simply supported with the precast-prestressed beam carrying all dead load and the beam-slab combination resisting live load.

Many structural and maintenance advantages can be claimed for prestressed construction, but it has been used in Florida work only on a basis of contract cost competition with one of the conventional types. To date, in every case, the prestressed alternate has won the competition on every job on which it was allowed. Experience has been so consistently good that the policy of designing alternate types is being abandoned for projects on which prestressed members are applicable. Recently, no bid was offered on the conventional types for several important jobs with keen competition.

The use of prestressed members in Florida bridges began in 1951 when a design was allowed in competition with two conventional types for $3\frac{1}{2}$ miles of trestle in the lower Tampa Bay bridge. The prestressed design was bid at a saving of about 4 percent. Little prestressed planning was done for a period of about two years during which time the Tampa job was tested and evaluated and found to justify both the structural computations and the contractor's cost estimates.

In 1953, there was an acceleration in prestressed planning occasioned by the design of several long trestle bridges and by the establishment of several large pretensioning plants. The latter development is of special significance as these yards have facilities for making many types and sizes of members economically in large or small quantities; therefore, the use of prestressed members is practical and economical for the small jobs requiring only a few parts.

The design of prestressed beams has been standardized insofar as possible. Figure 1 shows three sizes of beams designed to accommodate all loadings and all span lengths from 25 to 60 ft. In each size, the cross-section and end block details remain constant for various lengths, and lateral spacing in the structure is varied to satisfy the requirements of span and loading.
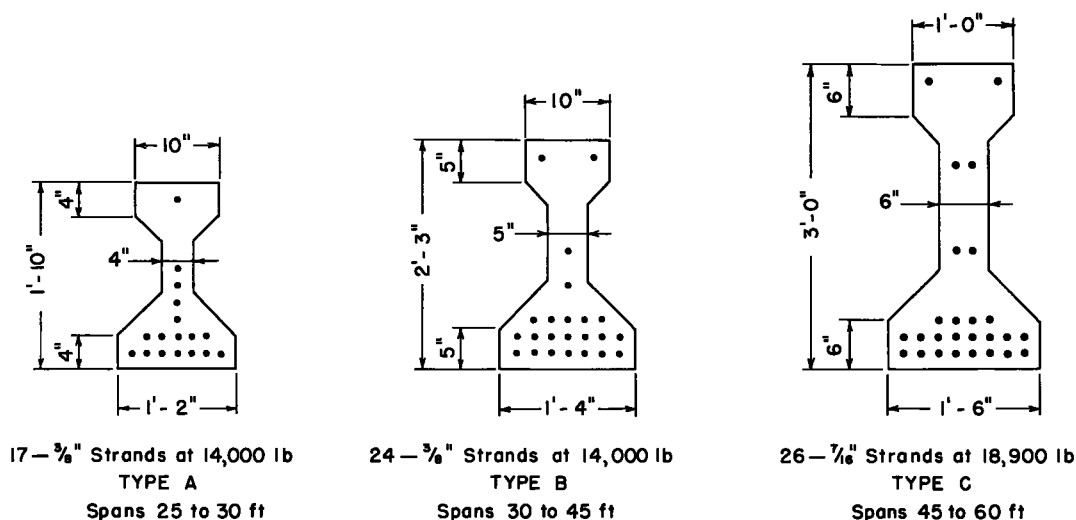
Figure 1. Standard pretensioned beams.

Standard beams for post-tensioning, as shown in Figure 2, have been developed for spans of 45 to 72 ft. These beams are an extension of the original design used for beams of the lower Tampa Bay bridge. They are also used with the combined method of stressing where the straight tendons are pretensioned and the draped tendons are post-tensioned.

Table 1 shows the bidding on ten typical projects of varied type, over-all length, and individual span length. A first cost differential, although of variable percentage, has been a consistent characteristic of bidding on these and all other jobs on which a prestressed design was offered. The superstructure cost includes all items above the substructure to, but not including, the handrail. The area upon which the cost per square foot is based includes the clear area of roadway and walks between the inside faces of railings.

Figure 2. Post-tensioned beams, cross-sections at mid span.

TABLE 1

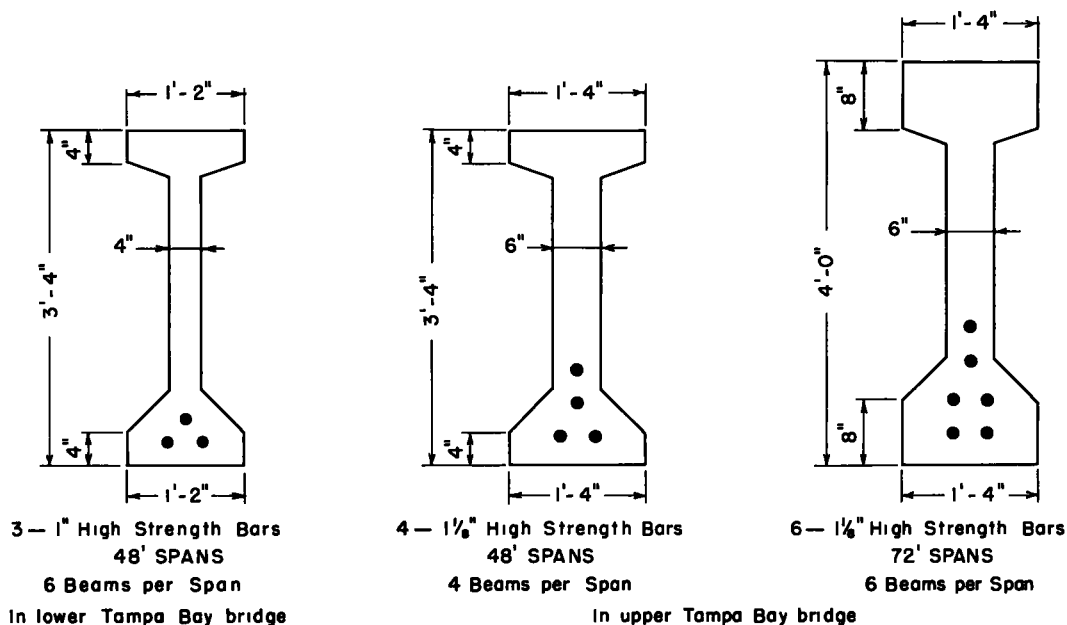| Bridge	No. and Length of Spans	Roadway Width	Walks	Type of Stressing	Superstructure Costs		Alternate		Date of Bids
					Per Lin Ft of Bridge	Per Sq Ft of Bridge	Type	Cost per Sq Ft	
Lower Tampa Bay	363 at 48'	28'	2 at 3'	Post.	$116.69	$3.43	Reinf T	$3.53	195
Cortez	50 at 48'	24'	2 at 5'	Combine	180.00	3.18	Reinf T	3.38	1954
Escambia River	71 at 36'	28'	2 at 2'	Pre	94.45	2.95	Reinf T	3.26	1954
Hillsborough River	8 at 53'	28'	2 at 2'	Pre	116.98	3.66	I Beam	4.66	1954
Upper Tampa Bay	252 at 48'	26'	2 at 1'-6"	Post.	87.96	3.03	Reinf T	3.59	1954
	20 at 72'	26'	2 at 1'-6"	Post.	166.67	5.75	I Beam	5.75	1954
Myakka Valley (6 bridges)	25 at 25'	24'	2 at 1'-6"	Pre	90.41	3.35	Reinf T	3.44	1955
Palm River	10 at 36'	56'	2 at 5'	Pre	314.77	4.77	Reinf T	4.85	1955
	1 at 45'	56'	2 at 5'	Pre	351.11	5.32	Reinf T	5.59	1955
Anclote River	7 at 45'	28'	2 at 3'	Pre	144.44	4.25	Reinf T	No bid	1955
Manatee River	30 at 66'	56'	2 at 2'	Post.	272.75	4.55	I Beam	7.32	1955
Palma Sola	72 at 48'	24'	2 at 5'	Post.	110.00	3.24	Reinf T	No bid	1955

A 106-mile section of the Florida Turnpike is now under construction from Miami north. Engineers for the turnpike commission have adopted the road department's standard pre-tensioned beams as alternates for I-beams for all structures on which they are applicable. As of December 15, 1955, bids have been received for 22 bridges on which the alternate was allowed. The bridges are principally grade separations or small structures of three or four spans with individual span lengths of 35 to 55 ft. On 9 of the bridges no bid was received for the I-beam alternate. On the remaining 13, the prestressed alternate was bid low in every case for a total saving of $93,000.

Some design features which tend to limit construction with prestressed beams are curves, warps, skews or other geometric requirements which result in highly variable lengths and shapes. Members for such specialized construction can often be best furnished through the fabricating facilities of the steel industry. In Florida, prestressed beams have not been used in spans skewed more than 20 degrees.

Pretensioning, with the reinforcement in a constant position on a bed several hundred feet long, is ideal for production line manufacture and minimizes the cost of stressing operation. Post-tensioning with part of the tendons draped to offset the variable dead load moment is more efficient. Relative savings between the two methods will vary between different jobs and different contractors. Limited experience on fairly large jobs has indicated that, for spans of more than 45 ft, the extra labor in stressing the draped tendons is more economical than the extra material required when all tendons are straight.

The limiting economic span length for this simply-supported composite construction is also difficult to define. Table 1 shows that a 72-ft span was bid at the same price with prestressed beams and with I-beams in 1954. This span was near the point of equal first cost for the prices prevailing at that time. Recent increases in the delivered price of fabricated steel have definitely increased this economic length. Bids for 1955 indicated a cost differential of steel above prestress of about 50 percent in 66-ft spans. These bids were by different contractors, and superstructure items other than the beams were involved. Possibly, any span in which the length would not be economically impractical for simply supported I-beams would be practical with precast-prestressed beams.

Prestressing, which was little more than an interesting probability five years ago, has become a firmly established practice and one that will become increasingly important in bridge and building construction.

Cost Comparisons of Prestressed Concrete vs Conventional-Type Highway Bridges

JOHN J. HOGAN, Consulting Structural Engineer
Portland Cement Association

● INCREASING use of prestressed concrete for bridges poses new problems to the bridge engineer. Each project must be studied as a separate entity unless the case involves a number of similar bridges.

Since the construction of the Walnut Lane Bridge in Philadelphia's Fairmont Park in 1948, the number of prestressed bridges constructed has been numerous. However, up to the present, little data on the reasons for their selection and the relative costs have been tabulated. Mere figures on the cost per square foot of deck area do not tell much unless some pertinent facts are known about the geological location, site conditions, number of beams used, fabrication, plant locations, transportation distances, and availability of contractors willing to bid prestressed concrete projects, since all of these factors play a part in the analyses of cost data.

In New York State, the first prestressed bridge was built for the town of Orangeville, near Warsaw (Figure 1).

It was not a large project, the span being 62 ft and the width 22 ft plus curbs and railing. The four girders were fabricated at the site over the stream bed with one set of forms. After the deck slab was placed, the bridge was prestressed transversely. The total cost of the superstructure based on an area of 64 ft by 25 ft was $8.35 per sq ft.

The experience and cost data derived from this project stimulated the county to continue their program of prestressed bridge construction. New schemes were developed and studied to attain two basic results: the precast units should be of such weight and size that they could be handled and transported with the equipment already available; and in the winter months, available county forces should fabricate units inside a heated building. The units could be stockpiled in the yard for erection in the spring and summer months.

The forms used on the first prestressed bridge were re-claimed and erected in the shop for the fabrication of similar girders (Figure 2). This time the girders were made in sections 17 ft 3½ in. long, 36 in. deep with a top flange 33 in. wide and a 12-in. web. After the end section was cast, the flexible tubing forming the holes for the prestressing units was withdrawn and inserted a short distance back into the member at the interior end. The required slope for the cables was laid out, and the next section was cast against the first one. This sequence assured an accurate fit for the shear keys at the joint and the holes for the cables. The operation was repeated for the member at the opposite end.

In the spring, the precast members were shipped by truck to the bridge site. Temporary bents were erected to support the members while the prestressing cables were pushed through and tensioned. All cables were grouted solid to insure bond for their entire length. The openings between the girder flanges were then filled with concrete and the bridge deck was prestressed transversely. Figure 3 shows one of the finished structures. The cost of the superstructure using this method was about $8.35 per sq ft for a deck area of 52 ft by 24 ft.

Since the county has a large number of short span bridges in need of replacement, a scheme was developed for fabricating this type. Solid slabs 2 ft wide, 12 in. thick and about 25 ft long were cast and prestressed in the shop. Each plank was prestressed with three cables of 12 wires each.

These slabs were later erected side-by-side on a prepared bridge seat to form the bridge deck. After the keys between the units were filled with mortar, the deck slab was prestressed transversely.

Figure 4 shows the finished bridge. The cost of the deck using this method averaged $2.70 per sq ft for a deck area 25 ft by 24 ft.

In October 1953, the New Jersey Highway Authority received bids on Section 11,
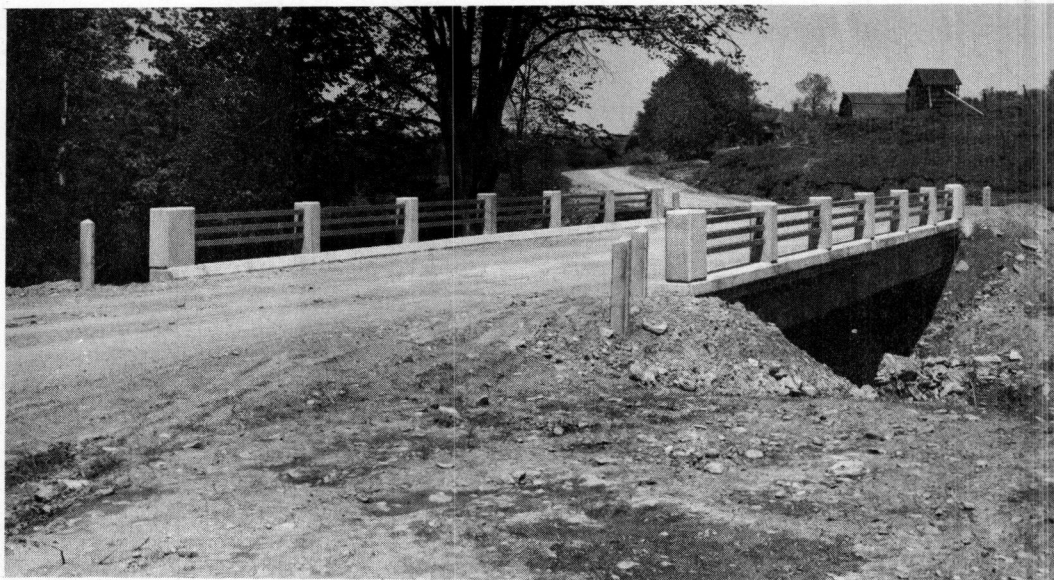
Figure 1. Bridge No. 10, Orangeville, New York.

Contracts 28 and 31 of the Garden State Parkway. This eight mile section is west of Atlantic City and is part of the 165-mile north-south toll road. In this contract, a total of 12 bridges was included for 8 grade separations. Bids were invited for reinforced concrete T-beam construction and for an alternate with prestressed concrete beams and cast-in-place concrete deck. Estimates showed the cost of the two types of construction to be about equal. However, contractors submitted bids only on the prestressed alternate.

The designing engineers worked out a scheme for the prestressed design to standardize the beam section irrespective of span length. This was achieved by selecting an I-shaped section which would fit the average span. By varying the number of steel tendons in the beams and the beam spacing in the bridge, it was possible to simplify the fabrication. The typical interior beam was I-shaped, 33 in. deep, 6-in. web, 12 in. wide top flange, and 19 in. wide bottom flange. Fascia beams were rectangular in section to meet requirements for a smooth exposed surface. These members were 33 in. deep and 16 in. wide.
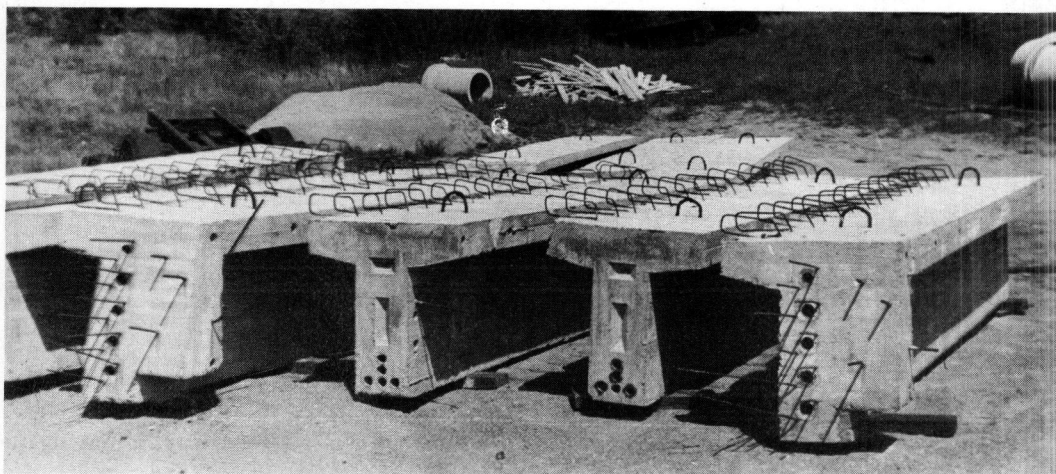
Figure 2. Precast beams for Bridge No.7, Pike, New York.

Figure 3. Bridge, No. 7, Pike, Wyoming County, New York.

The design assumed that the beams would carry all of the dead load during construction to eliminate the need for falsework. For live loads, the deck slab was included as part of the compression flange of the beams. Composite action was developed through the medium of shear keys and conventional stirrups. All of the beams were designed initially for pretensioning. In order to meet tight delivery dates for the construction schedule, the fascia beams were post-tensioned. The low bid was $7,777,777 for the entire work on the eight mile section. The concrete mix was designed so that a 2-day casting cycle could be maintained. Three hours after the concrete was placed, steam was introduced under tarpaulins to the concrete and a temperature of 140 F was maintained for at least six hours. The steam was then reduced and some steam was continued up to the time of stripping the forms and cutting the wires (Figure 6).

When the control cylinders cured with the beams reached a minimum strength of 4,000 psi, the tension on the strands was released and the strands were cut between the

Figure 4. Bridge No. 14, Perry, Wyoming County, New York.
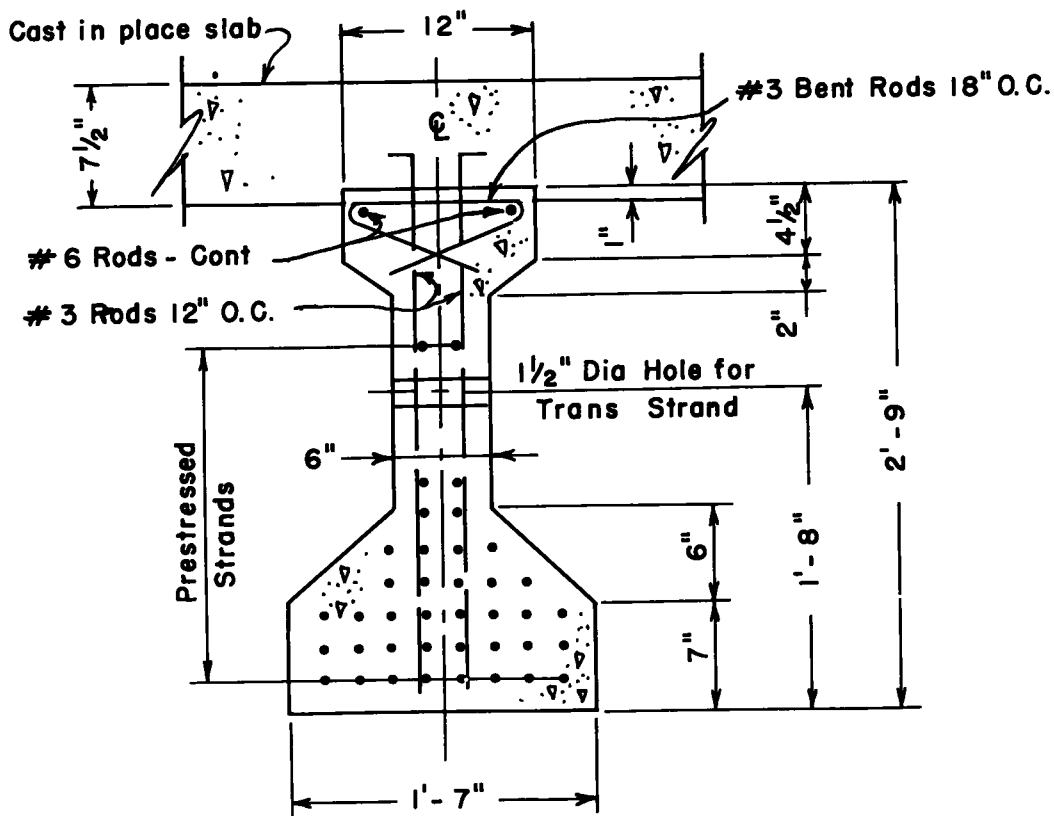
Figure 5. Garden State Parkway, N.J., Section II, Contract 28-31, prestressed girder detail (interior).

TABLE 1

GARDEN STATE PARKWAY — PRESTRESSED GIRDERS

Section 11 Contract 28 and 31

Crossing	Span C-C ft	Beam Length ft	Roadway Width ft	Interior Beams		Fascia Beams	
				No. Req	Strands[a] in each	No. Req	Cables[b] in each
W. Jersey and Seashore RR	39	40	90	20	24	2	4
Blackhorse Pike Interchange (twin span)	48.8	49.75	24	10	32	4	7
Zion Road	50.2	51.17	40.2	20	34	4	7
Westcoat Road (2 bridges)	51.5	52.5	40.2	20	36	4	8
Washington Avenue	53	54	90	24	36	2	8
Delilah Road (2 bridges)	56.3	57.25	40	20	40	4	8
Blackhorse Pike (twin span)	57.8	58.75	90	52	40	4	9
Ocean Heights Avenue (2 bridges)	60.4	61.4	40	24	40	4	9

[a] Interior beam strands ³⁄₈-in. diameter made up of 7 wires, total area 0.0799 sq in.
[b] Fascia beam cables ¼-in. diameter wires with "button heads" at each end (10 wires).

beams. This operation was usually done 18 hours after the concrete was placed. At 28 days, the concrete cylinders had reached a strength of well over 5,000 psi. The beams were moved from the casting bed by an overhead crane and stockpiled (Figure 7). When required, the beams were shipped about 30 miles to the bridge sites by trailer truck and erected by a mobile crane (Figure 8).
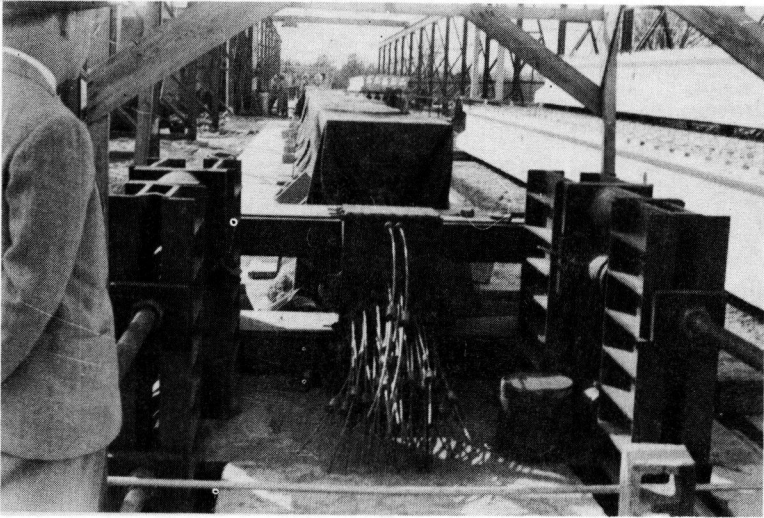
Figure 6. Prestressed beams curing in the prestressing bed, Garden State Parkway bridges, Section II.
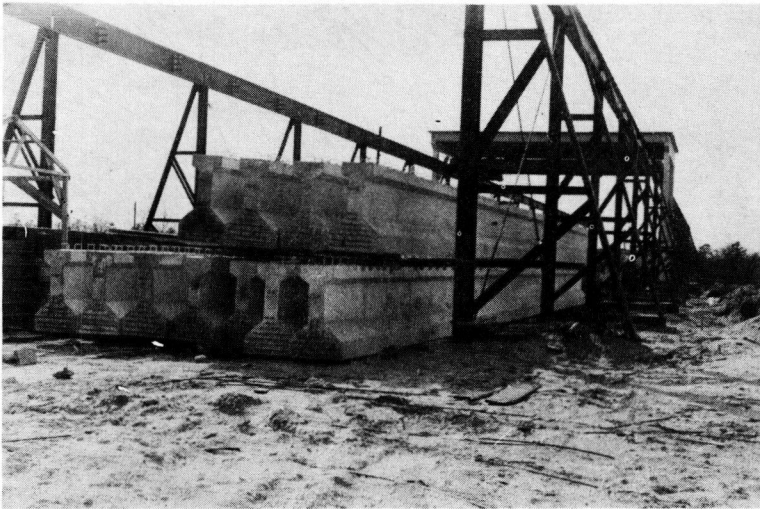
Figure 7. Prestressed beams stored at the casting yard, Garden State Parkway bridges, Section II.

Diaphragms were cast integrally with the $7\frac{1}{2}$-in. concrete deck slab. These were located at the ends and near the third points of the spans. Provision was made for prestressing the diaphragms transversely with a single cable in a flexible conduit at the third points. After the prestressing operation, the cable was grouted.

The prestressed beams were bid on a lump sum basis based on the different lengths required. Analyzing the bid data, the superstructure cost average $9.00 per sq ft. The prestressed beams ranged in length from 40 to 61.5 ft, and their cost averaged

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slightly over $5.00 per sq ft of deck area. The average cost per lineal foot per beam amounted to $20.50 with a variation range from $19.80 to $21.60 per lineal ft (Figures 9 and 10). Table 1 shows the data on the beams used for the various locations.

In September 1954, the engineer for Mercer County took alternate bids for the construction of the Sweet Briar Avenue Bridge. This bridge replaced a four-span all-

Figure 8. Prestressed beams erected at site over US 322, Garden State Parkway bridges, Section II.

TABLE 2

GARDEN STATE PARKWAY — GREAT EGG HARBOR BRIDGE

Section 11, Contract 173

	Alternates and Bid Prices					
	Alternate A Completion June 1956			Alternate B Completion December 1955		
	Method 1		Method 2	Method 1		Method 2
	1st Option 25' Span	2nd Option 40' Span	40' Span	1st Option 25' Span	2nd Option 40' Span	40' Span
Bidders	Prestressed Slabs	Prestressed Girders	Structural Steel Girders	Prestressed Slabs	Prestressed Girders	Structural Steel Girders
A	-	$2,289,788	$2,289,980	-	$2,758,545	$2,747,976
B	-	2,495,537	2,490,807	-	2,645,270	2,640,256
C	$2,622,317	-	2,649,362	$2,884,549	-	2,914,298
D	-	2,644,075	2,672,957	-	3,701,706	3,742,143
E	-	2,887,854	2,896,624	-	3,234,396	3,244,218

timber structure 24 ft wide that had been causing excessive maintenance. The new bridge (Figure 12) has three spans 18, 29, and 18 ft long, 50 ft wide on a 20 degree skew.

Bids were asked on designs in structural steel and prestressed concrete. The structural steel design called for 16- and 18-in. WF stringer beams, 4 ft on centers, with an open-deck steel-grid flooring 3 in. thick. The prestressed design (Figure 11) called for precast, prestressed T-shape units, which had a 22-in. wide top flange, $5\frac{1}{2}$-in.
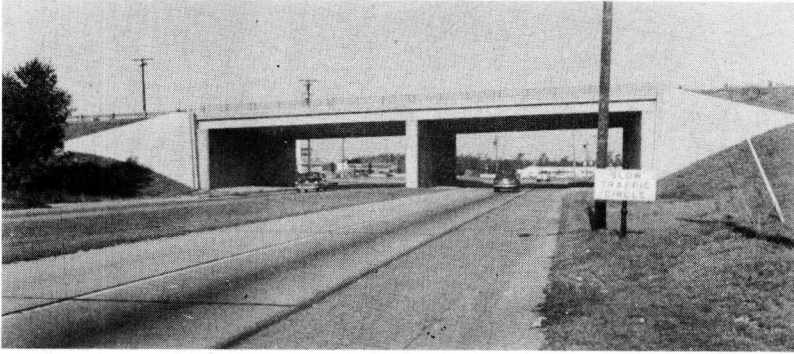
Figure 9. Two-span prestressed bridge over Route 40, Garden State Parkway bridges, Section II.

Figure 10. Single-span prestressed bridge over Route 559, Garden State Parkway bridges, Section II.

web, and a depth of 1 ft 6 in. These units were placed side-by-side and partially prestressed transversely through the diaphragms. A concrete deck slab varying in thickness from 3 in. to 5 in. at the crown was used as a wearing surface over the beams.

The low bidder submitted equal prices for the two schemes and the choice of construction had to be made by the county on some basis other than cost. The county selected the prestressed design because of the faster delivery of the prestressed beams and an estimated saving in painting cost for the steel structure. The cost of the superstructure was $6.90 per sq ft of deck area.

In October 1954, the New Jersey Highway Authority received bids for the construction

of the Great Egg Harbor Bridge (Section 11, Contract 173) which is also part of the Garden State Parkway. This section joins Beesleys Point to Somers Point in Atlantic County. The work consisted of the substructures (including abutments, piers, and wing walls) trestles, and bridge decks of two structures which carry the parkway across portions of Great Egg Harbor Bay.

TYPICAL SECTION

ELEVATION AND SECTION OF PRECAST DIAPHRAGM
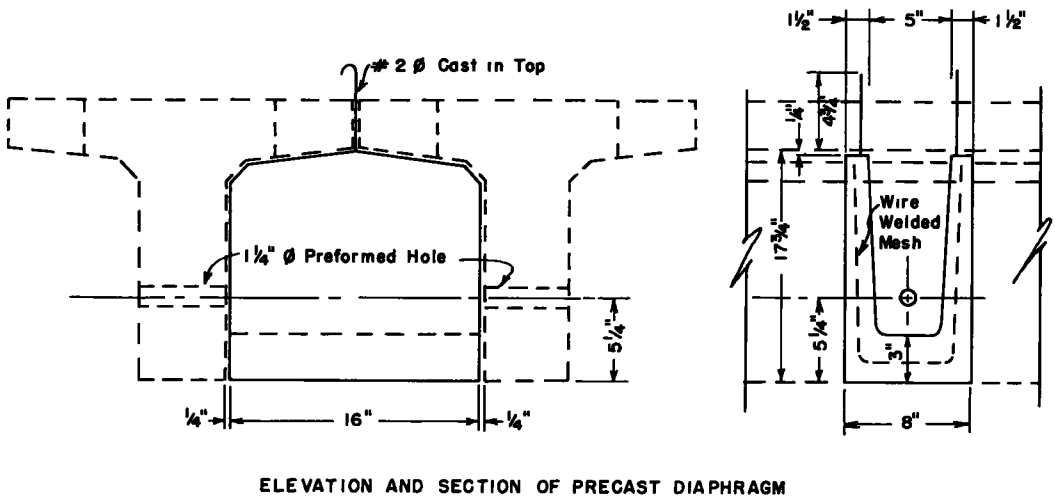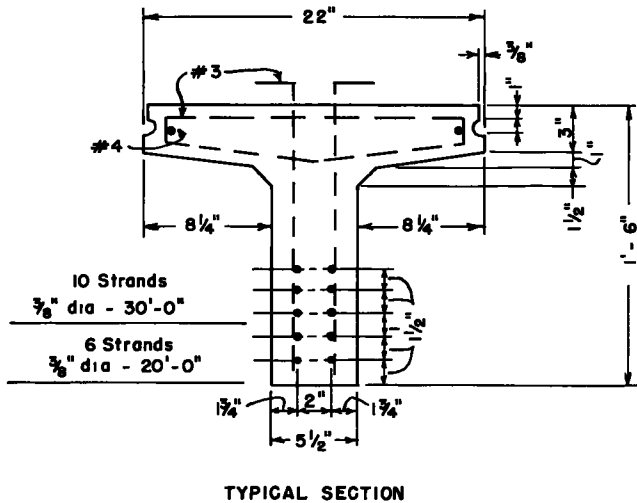
Figure 11. Typical cross-section of prestressed concrete T beam, Sweet Briar Ave Bridge, Trenton, N.J.

The south structure (Figure 13) starts at Beesleys Point, crosses Great Egg Harbor, and extends northward for about 3,650 ft to join a causeway to be built under another contract. The north structure, 750 ft long, (Figure 14) connects with the causeway, crosses Drag Channel, and ends at Somers Point.

Bids were invited on Alternates A and B. A completion date of June 1956 was set for Alternate A while Alternate B had a completion date of December 1955 (Table 2).

Each alternate was sub-divided into Method 1 and Method 2. In Method 1, the contractor could bid on precast prestressed slabs 25 ft long, 13 ft wide, and 12 in. thick. He could also bid on prestressed girders 40 ft long with a cast-in-place concrete deck.

These two schemes were listed as Option 1 and Option 2. A selection had to be made between one or the other for bidding.

Under Method 2, the contractor could bid on structural steel stringer beams with a cast-in-place concrete deck. The same scheme applied to Alternate B except the difference in the completion date. The schemes and bid prices are tabulated in Table 2.

The low bidder selected Alternate A, with the 40-ft spans. The difference in the low bid prices was $8,808 in favor of Method 2, Alternate A. The construction contract
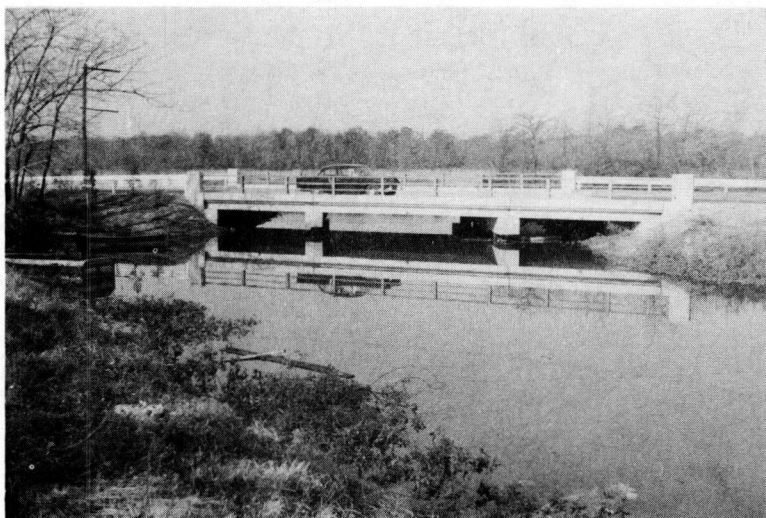
Figure 12. Sweet Briar Ave Bridge over Miry Run Creek, Trenton, N.J.
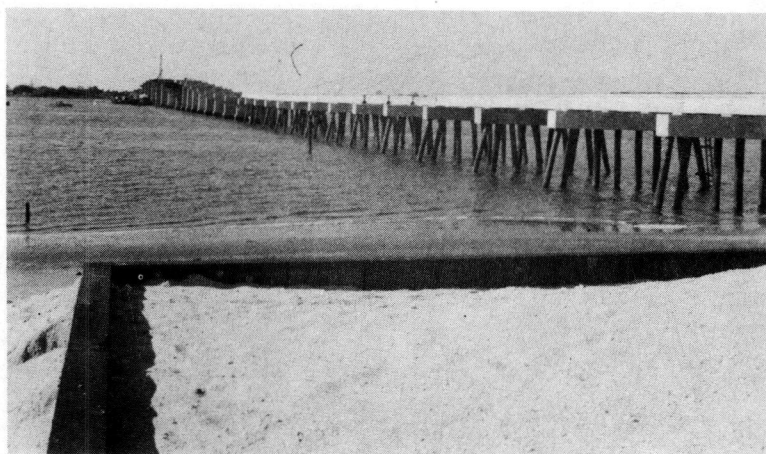
Figure 13. Great Egg Harbor Bay Bridge (looking south), Garden State Parkway, N.J.

was awarded to prestressed concrete on the basis of lower maintenance.

A review of the bid sheets shows that the 168 prestressed beams, each 40 ft long, were bid at $16.00 per lineal ft. The cost of the beams for the deck area averages less than $2.00 per sq ft. The approximate cost of the superstructure was $6.75 per sq ft of deck (Figure 15). The prestressed I-beams were 33 in. deep with a 6-in. web, 12 in. wide top flange, and 19 in. wide bottom flange. The beams were prestressed with 42 $\frac{3}{8}$-in. diameter strands. Four beams were used in cross-section to carry a 26-ft roadway curb-to-curb, with an over-all width of 32.5 ft. Composit action was developed between the prestressed beams and the 8-in. concrete deck slab through shear keys in

the top of the beams and stirrups.

In October 1954, the Virginia Department of Highways received bids for the 23-mile bridge and tunnel project connecting Hampton Roads with Norfolk. The construction included 7,470 ft of tunnel and two bridges 3,250 ft and 6,110 ft in length. The north-
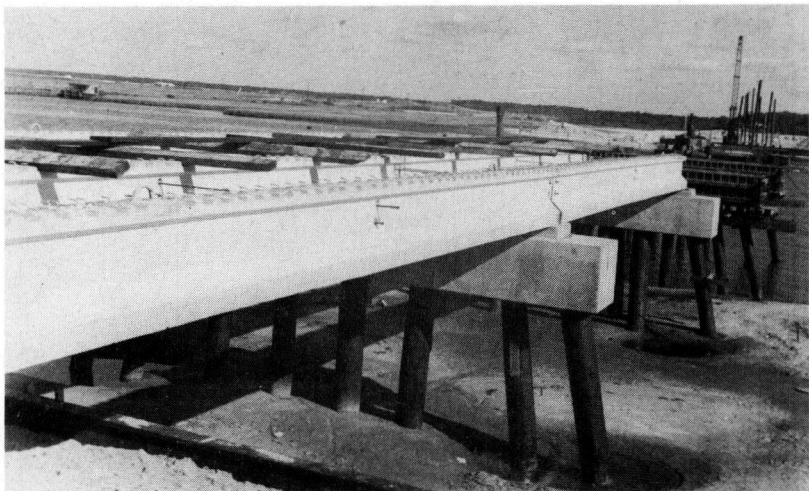
Figure 14. Great Egg Harbor Bay Bridge over Drag Channel, Garden State Parkway, N.J.

Figure 15. Great Egg Harbor Bay Bridge (looking south). Deck slab forms being erected, Garden State Parkway, N.J.

approach trestle, connecting Hampton Roads with a man-made island in the bay, was to be 3,250 ft long with a 30-ft roadway and a total width of 36 ft. The south-approach trestle, connecting Norfolk with another man-made island in the bay, was to be 6,110 ft long with a 30-ft roadway and a total width of 36 ft. The under-water tunnel was to connect the two islands.

The construction work was divided into two sections, one part for the tunnel work and the second part, designated as Contract C-2, for the north- and south-approach
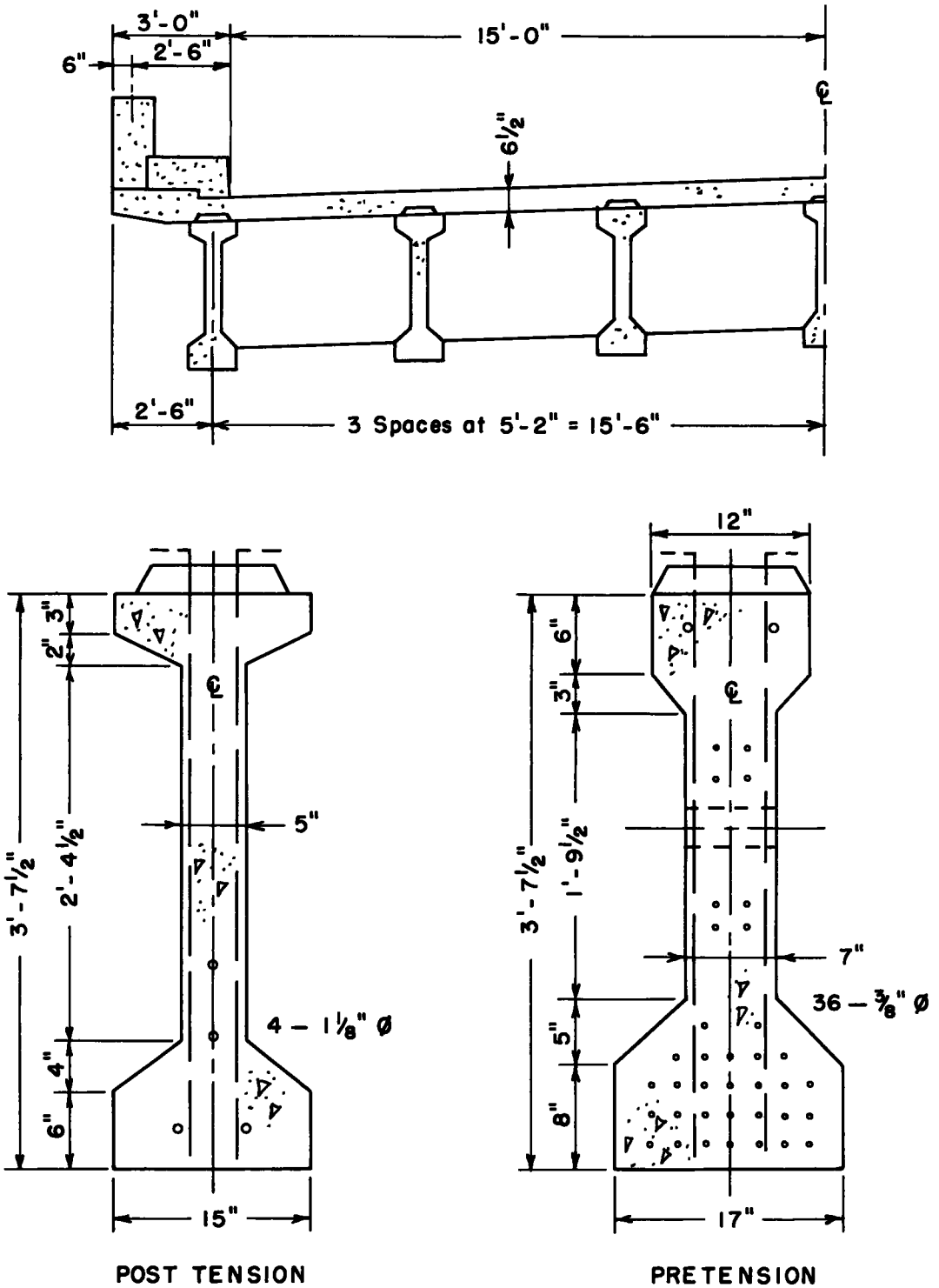
CROSS - SECTIONS, 50' SPAN

Figure 16. Commonwealth of Virginia, Department of Highways, Hampton
Roads Project.

TABLE 3
SUMMARY OF COST COMPARISONS - PRESTRESSED BRIDGES

Date	Project	Location	Span ft	No. of Bridges	No. of Spans	Crossing	Beam Cost Sq Ft Deck	Superstructure Cost Sq Ft Deck
1951	Wyoming County	Orangeville, N. Y.	62	1	1	Stream	-	$8.35
1952	Wyoming County	Pike, N. Y.	52	2	1	Stream	-	8.35
1953	Wyoming County	Perry, N. Y.	25	4	1	Stream	Plank	2.70
1953	Garden State Parkway	Atlantic City	39-60	12	1 and 2	Grade Separations	$5.00	9.00
1954	County	Trenton, N. J.	18-29-18	1	3	Stream	-	6.90
1954	Garden State Parkway	Egg Harbor, N. J.	40	1	42	Ocean Inlet	2.00	6.75
1954	Hampton Roads	Norfolk, Va.	50	1	128	Ocean Inlet	1.60	4.25
1954	Hampton Roads	Norfolk, Va.	80	1	37	Ocean Inlet	2.45	5.50

bridges. The north-approach bridge was designed for prestressed concrete, using 50-ft spans, seven beams in cross-section, and a 6½-in. concrete deck slab. Also designed in prestressed concrete, using 50 ft spans, was 3,150 ft of the south-approach bridge.

The remaining 2,960 ft of the bridge was designed for 80-ft spans, and this section could be bid in structural steel or prestressed concrete. These latter designs were designated as Alternate 1 and Alternate 2, respectively. The low bid was $19,050,461 for the entire project. The selection was Alternate 2. No bid on Alternate 1 was submitted.

The prestressed beam section bid for the 80-ft span was I-shaped, 4 ft 7½ in. deep, with a 1 ft 8 in. wide top and bottom flange, and a 5-in. web. This beam was reinforced with six cables, each having twelve 0.255-in. diameter wires. At the third points, the structure was prestressed transversely with two cables, each having twelve 0.255-in. diameter wires.

The 80-ft prestressed beams were bid at $1,000.00 each, concrete for the deck slab at $60.00 per cu yd, and reinforcing steel at $0.10 per lb. The cost of the prestressed beams was $2.45 per sq ft of deck area. For the superstructure, the cost averaged $5.50 per sq ft of deck area. For the 50-ft spans (Figure 16), the prestressed beams were bid at $414.00 each, concrete for the deck at $55.00 per cu yd, and reinforcement at $0.11 per lb. The cost of the prestressed beams was $1.60 per sq ft of deck area. The cost for the superstructure was $4.25 per sq ft.

Prestressed concrete piles were specified to carry the bents for the 50-ft spans. These piles were 24 in. by 24 in. with a 14-in. hollow tube in the center. The average length of the piles was 70 ft. For pile lengths of 70 ft and over, the vertical prestressing consisted of 32, 7-wire strands, each ⅜ in. in diameter. Piles shorter than 70 ft were prestressed, with 28, 7-wire strands, each ⅜ in. in diameter.

After the contract was awarded, the contractor requested permission to change the 80-ft spans to 50 ft and the standard-beam section was used. Also, the foundation design in the deep water area was revised and 54-in. diameter hollow prestressed piles were used. The wall of these circular piles was 5 in. thick, and the vertical prestressing consisted of 12 cables, with a wire area for each cable of 0.348 sq in.

The prestressed beams and piles were fabricated by the contractor at a site in Norfolk. Four 418 ft long casting beds were used for the project.

The summary of cost comparisons listed in Table 3 demonstrates that prestressed concrete for bridges offers economy in competition with other types.

The increasing number of plants now available to fabricate various types of prestressed sections assures the submission of bids by a number of contractors. At present, beams about 60 ft long seem to be the maximum length that can be shipped from plants over the highways. Longer lengths could be shipped by rail or water if the plant and site locations are suitable.

Site precasting has been used effectively for several projects in the eastern region. This method was generally used because of the number of units fabricated and the area

available for stockpiling. The relative cost of renting a large area near the project for site prestressing may in many cases prove more economical from the contractors' standpoint than using a plant where storage facilities are limited.

Standardization of prestressed units seems to be the trend at the present time. In the near future, it should be possible to purchase prestressed bridge units for various span lengths in beam and slab sections.

The scheme used on the Garden State Parkway bridges opens the field to further standardization of such sections. For short span bridges, prestressed solid and hollow slab sections will be available at fabrication plants for various spans and loading conditions. The recent floods in the east, where many bridges were washed out, demonstrated the need for units to replace such bridges in the shortest possible time.

From the construction standpoint, prestressed units offer an efficient and economical solution for bridge replacement. Through the medium of prestressed slab units, it is possible to replace an old bridge while maintaining traffic during construction.

On the longer spans, the use of prestressed concrete eliminates many of the problems with camber, when a partial width of the roadway is constructed in one operation. The need for building a variable haunch in the formwork for the deck slab is also eliminated. Since the prestressed girder is stiffer than other composite types and deflections are less, the need for falsework during construction is eliminated and vibration from traffic is less noticeable to pedestrians.

Much work remains to be done in the field of prestressing continuous structures, both in the design theory and construction. The possibilities of this method for long-span bridges seems promising. Today, contractors are bidding on prestressed designs with the same acceptance as other conventional designs. Like any new construction material or method, prestressed concrete must demonstrate its capabilities above and beyond its normal function before its full potential is exploited.

Prestressed Concrete in California

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California Division of Highways Bridge Department

●WITHIN the past six years, prestressed concrete in the United States has grown from an innovation into an accepted method of concrete construction. This growth, a result of a new application of existing materials and theories, is quite phenomenal. In Europe, during the past ten years, shortages of materials and enforced economies in construction have given prestressed concrete a substantial start. The development in the United States, however, has been somewhat slower. Its acceptance has been characterized by some hesitancy, both on the part of designers and contractors, mainly because of lack of experience and reluctance to abandon methods of construction for which they were well experienced and equipped. There have also been difficulties and misunderstandings concerning the various anchorage systems and types of stressing units.

However, there has been much progress. Experience came rapidly, and the quality of the work improved. With increased know-how, the work became easier and the prices dropped.

Each prestressed concrete job still provides new problems and consequently adds to knowledge of the subject. Prices have not dropped to their ultimate level; the drop so far has been merely sufficient to bring prestressed concrete within the range where it can be used occasionally on a straight economic basis without justification by some other advantage peculiar to prestressed concrete. Prices have not yet reached the point where prestressed concrete can be substituted with impunity for conventional concrete design. Contractors still have their own equipment; the crews are trained for conventional construction. In California, they usually bid rather high on prestressed concrete work for which they must secure outside experts or rent special equipment.

Fittings, Patents and Salesmen

The increasing acceptance of prestressed concrete has led many manufacturers into the production of the prestressing rods, wire and cables, and especially the end connections for the tension members. Almost every conceivable method of fastening the wires and rods has been tried. Many methods are covered by patents, and each of the several systems available has its own advantage. The strenuous competition has in some cases acted to the detriment of the prestressed concrete field as a whole.

Designing for specific systems is not a desirable policy on public work. Designs must be prepared with sufficient latitude so that any of the leading prestressing methods may be applied to the work. This often results in oversize beams and end details which are cumbersome or undesirable.

A general contractor making the low bid on a structure containing prestressed elements is immediately besieged by salesmen offering different prestressing systems. Sometimes these systems and devices are new and untried, and the unwary contractor may find that he is paying a sub-contractor to perfect some new device that may or may not be successful. Such tactics do not generate confidence in contractors nor encourage reductions in prices.

Unfortunately, the contractor may not combine the best features of several systems to his own benefit and to the benefit of the job, but he must choose one system to follow through — accepting both its advantages and its disadvantages. The use of the equipment is often tied in with the use of a particular anchorage system because the equipment is specialized and the know-how is still not too widely dispersed.

These factors acted somewhat to the detriment of the prestressed concrete development.

Jacks and Grouting Equipment

Some efficient jacks and holding devices have been developed to do the stressing work on the tension members. The jacks are usually made and operated by the purveyor of a certain type of fastening device so that the advantages or disadvantages of a

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given type of jack are tied to the chosen type of anchorage.

Although the grouting of the cable or rod enclosures is generally considered to be of vital importance (either from a corrosion protection standpoint or occasionally from the standpoint of achieving full bond), the grouting equipment is often makeshift and impractical. In the early stages of prestressing work, some jobs were halted because of inadequate grouting equipment.

It is pertinent to the economics of prestressed concrete to point out that adequate and efficient methods of grouting the prestressing members must be developed and used generally. This is essential to make prestressed work competitive. Many contractors, although the actual prestressing work may be handled by some subcontractor, shy away from bidding this type of work, or else bid quite high, because of known difficulties with the grouting operation. As long as such factors influence a contractor's bid, the prices for prestressed will remain high.

Post-tension or Pretension?

Prestressed concrete was first introduced through post-tensioned members, but the economic benefits of pretensioning became apparent, and suppliers began to equip themselves to manufacture pretensioned beams.

The possibility of procuring standard prestressed concrete beams from a supplier in the same manner as steel or timber beams is rapidly becoming a reality. After some experimenting with various sections, bridge members are now being standardized so that suppliers will find it economical to provide semi-permanent forms for repeated use.

The benefits of casting pretensioned beams, slabs, and piles on beds as long as 500 ft, steam curing them in place, and then cutting them apart and moving them in as little as 24 hours have already been realized. Large beams also have been simplified by pretensioning. Where the needed prestressing force exceeds the capacity of the tensioning bed, it has been possible to pretension the beam enough to permit moving and, then, add the remainder of the prestressing force by post-tensioning.

The full possibilities for pretensioned concrete manufactured in a plant and sold as a stock commodity are yet to be realized. The basic requirement is that precast pretensioned work requires a precision and attention to detail not involved in concrete work before. With care, excellent work can be and is being done. Greater facility on the part of the manufacturers and greater acceptance on the part of the designers will make this phase of prestressing one of its most interesting developments.

Precast Concrete

Some thirty years ago, the concrete industry became aware of the possibilities of precast concrete work. There was a period when efforts were made to utilize precast units to the fullest, but carrying the method to the point of precasting every part of a structure led to its decline. Structures without adequate joint rigidity eventually collapsed, and the use of precast work fell to a minimum.

Once again the benefits of precasting — the benefits of doing the expensive forming and pouring work in a central yard — are being discovered. Precast work must be designed with full knowledge of the necessity for joint rigidity. The designers must realize that there are practical limits to precasting and that present day structures must be designed with the provision that some of the concrete be poured in the field to tie the members together.

Cost Comparisons with Conventional Designs

The purpose of this paper is to make a definite comparison of the costs as realized to date on some California projects with the cost of conventional design.

California's five years of experience do not offer conclusive evidence on the comparative cost of prestressed and conventional concrete construction.

Since September 1950, when bids were taken for the Arroyo Seco Pedestrian Bridge in Los Angeles, twenty projects have been built using various types of prestressed units.

Approximately the same number of projects are being designed for construction within the next three years.

Prices are available for the twenty completed structures, and an attempt has been made to compare each prestressed concrete structure with a similar structure of conventional design. These twenty structures are composed of a variety of types of prestressed elements. The twenty projects were divided as follows:

Number of Structures	Prestressing Application
2 pedestrian overcrossings	T-shaped girders
1 pedestrian overcrossing	Slab
6 structures	T-shaped girders
1 structure	Inverted T-section
2 structures	I-shaped girders
3 structures	Precast channel sections
1 undercrossing	Slab
2 structures	Box girders
2 miscellaneous structures	Caps and beams

Prestressed concrete is not practical in all situations. Like all other materials, there are special advantages of the system which make it better in one situation than in another. It is of special interest, therefore, to analyze the reasons for selection of prestressed concrete designed for these various structures.

In seven of the cases, prestressed and precast concrete was chosen so that the beams could be swung into place either over water or over traffic with a minimum of interference. Economy and elimination of falsework were the main benefits.

In six cases, the prestressed design was chosen for separation structures to reduce the depth of the member to a minimum and to maintain the maximum clearance between roadway grades. Precast and prestressed construction was chosen in three cases because of the advantages and saving made possible by the mass production of a large number of similar units. Another saving is to be found in construction without falsework.

Three more bridges were made precast and prestressed because of their remote location. It was more economical to precast the elements of the bridge at a plant and haul them out to the job than it would have been to transport all of the component parts and the labor.

The inherent characteristics of prestressing made it suitable for the twentieth structure. A bridge which was to be loaded with three feet of superimposed fill was bolstered up underneath with prestressed beams. The prestressing of the supplementary beams created a camber which brought them into firm contact with the original structure, enabling them to take their intended share of the increased load. This characteristic is also being used in several other structures now being designed. It is far superior to wedging or dry-packing with grout.

One of the difficulties in comparing prestressed concrete structures with conventional designs is that the prestressed type of design is often chosen to satisfy some particular condition for which there is no equivalent in conventional design. An example is a prestressed design chosen to save headroom in a separation structure. In the case of the Hoppow Creek project, for example (Figure 2), the use of prestressed design enabled the depth of girder to be reduced to 27 in. for the 50-ft spans. A conventionally designed T-beam for a 50-ft span would run 42 to 48 in. deep. Since the depth of girder is important at this location, it becomes a factor in making a fair comparison. If the prestressed girder could be made only 26 in. deep, should not the comparative cost of a conventional design also be figured upon a T-beam only 26 in. deep? A comparison of this sort does not present conventional concrete design in its most efficient form.

The comparisons made in this discussion are based upon the most economic use of the two designs. If the conventional design has a greater depth than the prestressed design, it is presumed that the approach grade line will have to be raised to compensate. Although this raise in grade may introduce additional costs chargeable to the conventional design, only the actual cost of the two superstructures is considered.

COMPARISON

PRESTRESSED

Bacon St. Undercrossing
IV-SF-68-SF(x)

|2'-2"

|← 98'-0" →|

Working Force - 196,000 #/ft width

CONVENTIONAL

Hypothetical
Similar Design

2'-8"

|← 98'-0" →|

62'-6"	SPANS	62'-0"
6114 sq ft	AREA OF DECK	6114 sq ft.
$40,580.	COST OF SUPERSTRUCTURE	$40,250.
$6.65	COST PER SQ FT	$6.58
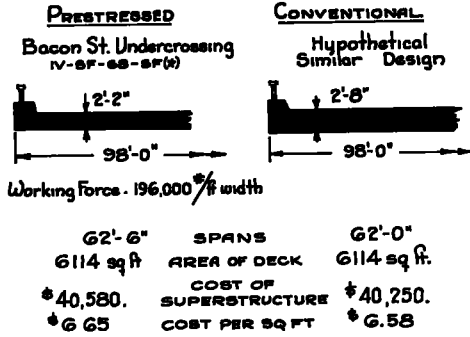
Bids rec'd- 5-53

(x) California Location Code:
(Highway District)-(County)-(Route)-(Section).

Figure 1.

A number of the applications of prestressed principles were of such a specialized nature that comparison to a conventional design is not possible. These have been eliminated from consideration. There are twelve structures on which it is possible to make a cost comparison.

Nine of the structures are compared to conventional structures which are very closely parallel in span and site conditions. To make a comparison for the other three structures, it is necessary to make a design for a hypothetical structure of the same span and width.

In making these comparisons, only the construction cost for the superstructure is used. Rail and curbing costs are not included. In order to obtain comparative cost per square foot, the areas of the structure are taken to be the rail-to-rail width multiplied by the distance from paving-notch to paving notch.

In the following comparisons a conventional design type is compared with one or more prestressed structures. The grouping is made with approximately equal span lengths. In order to consider only the relative initial structural costs (in the case where steel bridges are used as a comparison), the cleaning, painting and maintenance costs are not included. Where structures were in remote locations, some adjustment was made in order to compare with the cost of structures located closer to the sources of material and labor.

COST COMPARISONS

Slab Bridges

The Bacon Street undercrossing (Figure 1) is a prestressed concrete slab built in San Francisco in 1953. The bridge is wider than it is long, having a 62-ft span with a width of 100 ft. The thickness of the slab is 26 in. The slab was cast-in-place, and was post-stressed using wires grouped in sheaths, and was also prestressed laterally. The superstructure alone cost $40,580.00 for a deck area of 6,114 sq ft. The unit cost of the structure was $6.65 per sq ft.

Since no comparable bridge of conventional concrete design was available, a hypothetical design was made for a 62-ft slab span, reinforced in a conventional manner. The total cost of the superstructure was estimated at $40,250.00, making a total cost of $6.58 per sq ft.

The comparison shows the two types of designs to be almost identical in cost per sq ft. However, the conventional design would have required 6 in. more depth of slab, which extended to the approach fills would have materially increased the cost. Therefore, the prestressed design was chosen in order to cut the required headroom to a minimum and keep the grades of the two roadways as close together as possible.

Channel Sections

Three prestressed, precast structures having a channel section are compared to a conventional design T-beam (Figure 2). The Hoppow Creek project was built along the sparsely populated northern California coast. Prestressed construction was chosen for three reasons: (1) to get a minimum depth of superstructure so as to obtain as much waterway as possible without having to raise the roadway grade, (2) to obtain a structure which could be formed and poured where labor and materials were more plentiful, (3) to get a concrete structure which would require a minimum of maintenance in this damp location. Figure 2 shows the dimension of the section and the cost statistics of

COMPARISON

PRESTRESSED

Hoppow Creek
I-DN-48-A Bids: 4-'55
w = 3-7½" d = 2'-0"
s = 6" s₁ = 7" t = 5½"
Working Force = 360,000 #/gir
Span = 50'
Area of deck = 1808 sq ft
Cost Superst = $14,950
Cost per sq ft = $4.29 (adj)*

Route 20/1 Sep
I-HUM-1 BIDS 3-'55
w = 4-8¾" d = 2'-6"
s = 7" s₁ = 8" t = 5¾"
Working Force = 350,000 #/unit
Span = 46'
Area of deck = 1472 sq ft
Cost Superstr = $19,580.
Cost per sq ft = $5.14 (adj)*

Dry Creek Canal
VI-FRE-125-FRE BIDS 3-'55
w = 3-9¼" d = 2'-0"
s = 7" s₁ = 9" t = 6"
Working Force = 374,000 #/gir
Span = 44'
Area of deck = 3084 sq ft
Cost Superstr = $16,272
Cost per Sq ft = $5.28

CONVENTIONAL

South Petaluma UC
I-SON-1-F
28' Rdwy
6⅝"
3'-9"
1'-4"
5 girders @ 8'-0" %

Twin bridges

Spans = 26', 52', 36'
Area of Deck = 4174 sq ft
Cost of Superstr = $15,185.
Cost per Sq Ft = $3.63

Bids rec'd = 5-'54

★ (adj) — Prices for structures in remote locations have been reduced to make them comparable to locations closer to labor and material sources

Figure 2.

the structure. The prices were adjusted to make them comparable to locations closer to labor and material sources. The adjusted cost was $4.29 per sq ft.

The separation structure at the junction of California Routes 1 and 20 was built in 1955. The reasons for the choice of prestressed concrete were similar to those at Hoppow Creek. Figure 2 shows the details of the section and the adjusted price for this bridge was $5.14 per sq ft.

The third structure in this group was the Dry Creek canal bridge near Fresno. Prestressed design was chosen to allow setting the units in place over a full-flowing canal without the necessity of using falsework. The structure consisted of eighteen 44-ft precast channel sections bolted together and surfaced with asphalt. The approximate weight of each unit was 16 tons. Figure 2 shows the data on the section and the cost was $5.28 per sq ft.

For comparison, a conventional T-beam design has been used. The South Petaluma undercrossing, built in 1954, has five T-beams 45 in. deep. The undercross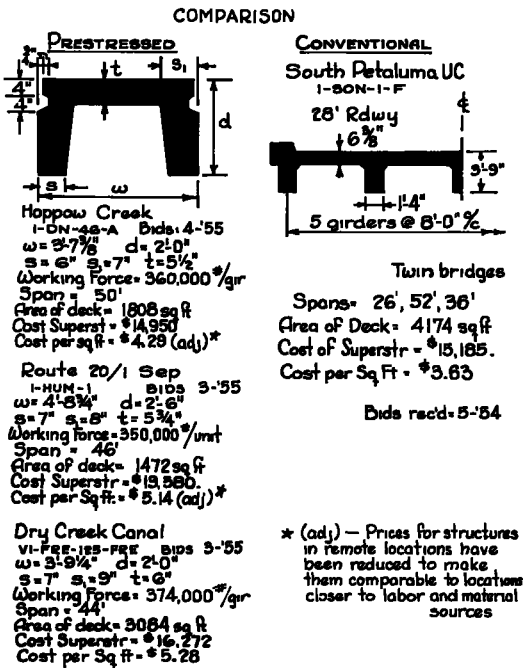ing consists of twin structures both of which are comparable to the three precast structures. The cost for this conventional T-beam structure was $3.63 per sq ft.

Although the unit cost of the latter is less, there are advantages to prestressed design which do not appear in the price. The cast-in-place T-beam required 15 in. to 21 in. more depth of girder, decreasing the headroom beneath the structure. Furthermore, the falsework had to be built for the cast-in-place structure, whereas the precast units were cast in a yard and hauled to the site. Although the cost of the falsework is included in the unit price, the advantages of construction without obstructing the channel or the roadway are not always reflected.

Precast "T" Sections

The Santa Maria River bridge (Figure 3) consisted of twenty-four 50-ft spans across a wide, flat, gravel river bed. The T-section girders were cast and post-tensioned on the river bank, then, hauled out and set into place. The saving in falsework was, to a degree, offset by the necessity for building a temporary casting yard on the river bank. One hundred twenty of the precast and post-tensioned girders were manufactured. The final unit cost for this superstructure was $3.53 per sq ft.

The Santa Ana River bridges (Figure 3) consisted of a conventional T-beam design used for parallel bridges. The span lengths were the same, and the river bottom condition was very similar to that at the Santa Maria River site. The Santa Ana River project has possibly a slight advan-

COMPARISON

PRESTRESSED

Santa Maria River
V-SLO-36-B
2'-9" 4'-4"
6"
3'-0" 7"
1'-3"
4"

5 lines @ 7'-1" %
Working Force 359,000 #/gir

CONVENTIONAL

Santa Ana River
VII-ORA-175-B
Rdwy 28' 3'-6"
7"
14"
4 girders @ 9'-0" %

Twin bridges

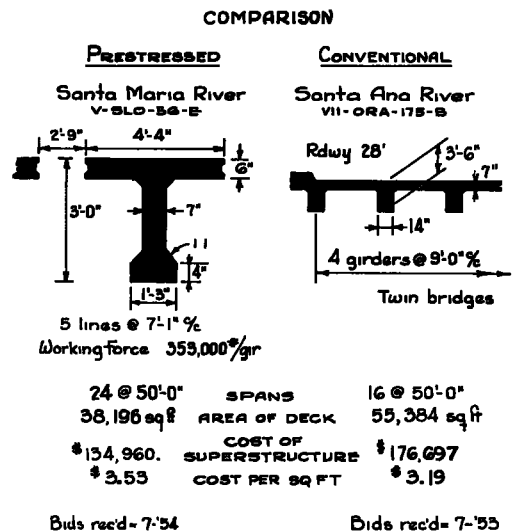|	PRESTRESSED	CONVENTIONAL
SPANS	24 @ 50'-0"	16 @ 50'-0"
AREA OF DECK	38,196 sq ft	55,384 sq ft
COST OF SUPERSTRUCTURE	$134,960.	$176,697
COST PER SQ FT	$3.53	$3.19

Bids rec'd = 7-'54   Bids rec'd = 7-'55

Figure 3.

tage in being somewhat closer to a large labor and material source. However, in this case the conventional T-beam design was cheaper than the prestressed and precast design. The cost for the Santa Ana River project was $3.19 per sq ft.

The Richardson Bay bridge (Figure 4) was built over an arm of San Francisco Bay where the bottom was covered with a thick layer of thin mud. Falsework would have been prohibitively expensive. The portion of the structure over the water was designed for prestressed and precast beams which were lifted into place from a derrick barge. The beams were cast in a yard which had water access to San Francisco Bay and were hauled about 40 miles to the bridge site. The operation was successful, and the unit cost for the precast portion of the bridge over the water was $3.94 per sq ft.

A hypothetical design was made to compare to the Richardson Bay bridge, with

Figure 4.

the presumption that, because of the falsework difficulties, it would be necessary to use steel welded girders even though, in this salt water location, the maintenance painting cost would be increased. Maintenance painting costs were not included in the unit costs for this study even though these costs must be included in an over-all economic study to determine the type of structure to be used. The hypothetical design cost, based upon prices for similar work, was $4.59 per sq ft, a material benefit in favor of the prestressed and precast construction.

In the separation structure (Figure 5) at the junction of California Routes 5 and 107, prestressed section was used to obtain the minimum depth of girder and was precast to get the advantages of construction without falsework. The unit cost was $6.00 per sq ft. The Collier Road overcrossing, with welded steel girders and a concrete deck had a unit cost of $5.09 per sq ft and was considerably cheaper than the prestressed structure. The primary probelm was one of erecting the structure over traffic, and the T-beam design minimized the amount of concrete form work which had to be done.

Figure 5.

I-Section Precast Girders

Figures 6 and 7 show I-section precast and prestressed girders compared with steel girders for comparable spans and conditions. In both cases, the precast concrete beam is slightly deeper than its steel counterpart.

The Grant Street undercrossing consisted of five girders 42 in. deep with a maximum width of 18 in. The beams were cast at the site and lifted into place. The unit cost was $5.15 per sq ft for the superstructure.

The Frontage Road overcrossing, using 36 in. wide flange steel beams, also had five girders and comparable spans. The cost of the superstructure was $5.98 per sq ft.

The other precast prestressed I-section was the Ocean Street undercrossing (Figure
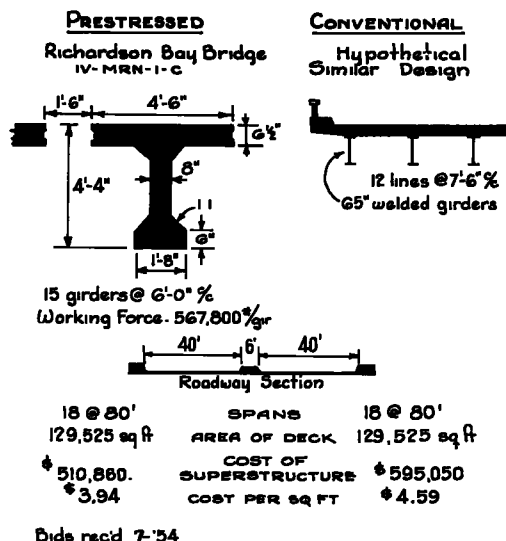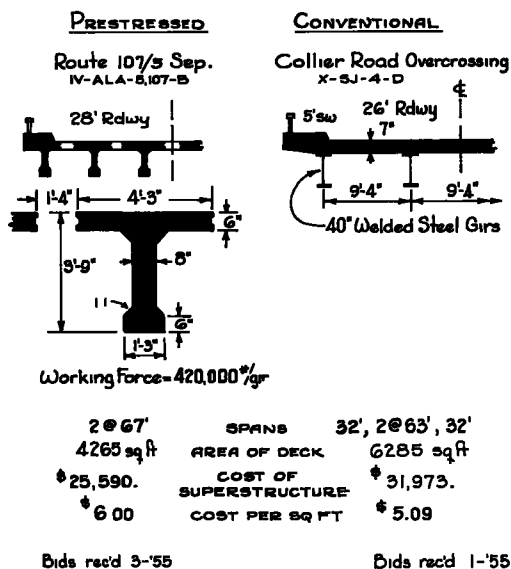
COMPARISON

PRESTRESSED   CONVENTIONAL

Grant St Underxing   Frontage Rd Over'xing
IV-SCR-56-SCR   VII-VEN-60-B

28' Rdwy   28' Rdwy

5 lines spacing varies 6'-6" to 7'-2"

Skewed & curved

Working force = 348,000#/gir

53', 2@59', 33'	SPANS	2 @ 50'
5426 sq ft	AREA OF DECK	3718 sq ft
$27,977	COST OF SUPERSTRUCTURE	$22,250.
$5.15	COST PER SQ FT.	$5.98
Bids rec'd 7-'55		Bids rec'd 5-'54

Figure 6.

COMPARISON

PRESTRESSED   CONVENTIONAL

Ocean St Undercrossing   Calaveras River
IV-SCR-56-SCR   X-SJ-4-C

28' Rdwy   4' sw one side
                         40' Rdwy

5 girders @ 6'-6" to 7'-2"   33 WF 220
                               6 girders @ 7'-9" %

Working Force = 348,000#/gir

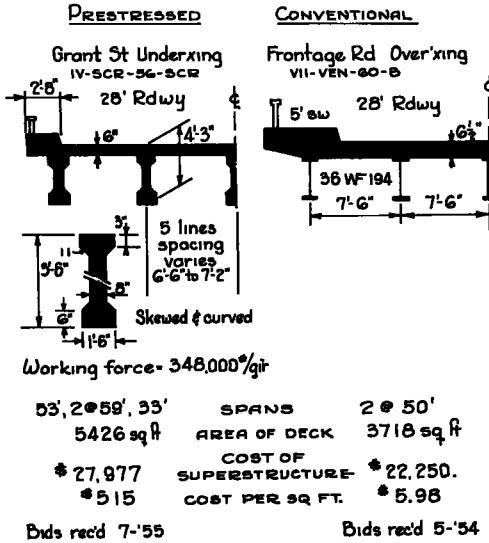| 49'-7", 47'-2" | SPANS | 40', 54', 40' |
3275 sq ft	AREA OF DECK	6220 sq ft
$15,044	COST OF SUPERSTRUCTURE	$31,100
$4.60	COST PER SQ FT	$5.00
Bids rec'd 7-'55		Bids rec'd 11-'47

Figure 7.

7). Its cost of $4.60 per sq ft was materially better than the cost of $5.00 per sq ft for the Calaveras River bridge. The Calaveras River bridge was made up of six 33 in. wide flange steel beams, and it had a somewhat wider roadway. However, on a square foot basis the prestressed structure was cheaper in both cases. In neither instance was the depth of girder a critical factor.

These sections represent pioneering efforts on the part of both designers and construction forces. One evidence of the state of flux in this new field is the variation in dimensions of the "I," channel, and "T" sections. Obviously, such variation is not an economical practice. It is essential that a standard section be adopted. California is now standardizing these sections.

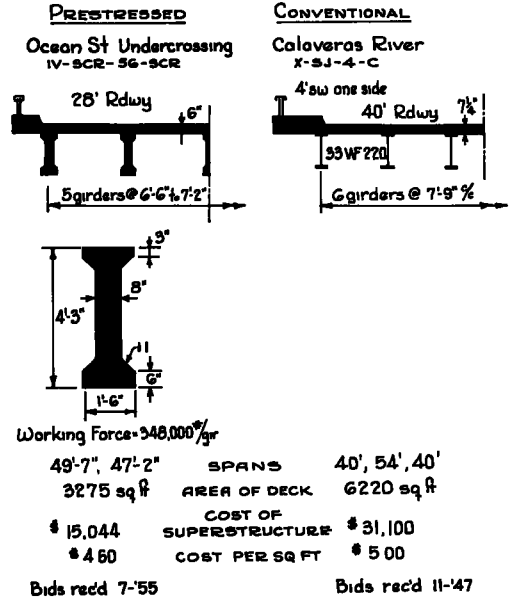## Bridges Prestressed in Place

Figure 8 shows a pair of concrete box girders, one of which was post-tensioned. The John Street overcrossing was the first
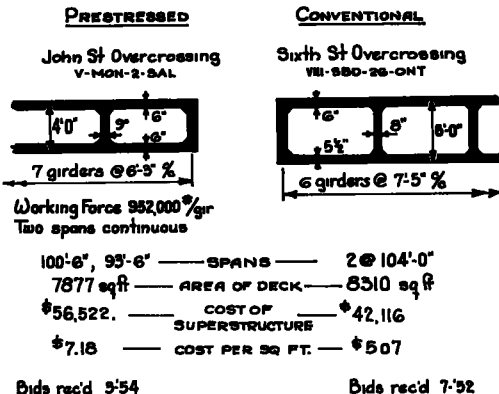
COMPARISON

PRESTRESSED   CONVENTIONAL

John St Overcrossing   Sixth St Overcrossing
V-MON-2-SAL   VII-SBD-26-ONT

7 girders @ 6'-5" %   6 girders @ 7'-5" %

Working Force 952,000#/gir
Two spans continuous

100'-6", 95'-6"	SPANS	2 @ 104'-0"
7877 sq ft	AREA OF DECK	8510 sq ft
$56,522.	COST OF SUPERSTRUCTURE	$42,116
$7.18	COST PER SQ FT.	$5.07
Bids rec'd 5-'54		Bids rec'd 7-'52

Figure 8.

COMPARISON

PRESTRESSED   CONVENTIONAL

Scott R @ Horn Lane   Hypothetical Similar Design
II-SIS-FAS

28' Rdwy   28' Rdwy

6'-0"   10" min   90" welded girders
                       10'

4 girders @ 8'-0" %

Working Force = 900,000#/gir

120'	SPANS	120'
3660 sq ft	AREA OF DECK	3660 sq ft
$26,790	COST OF SUPERSTRUCTURE	$33,400
$732	COST PER SQ FT	$9.12
Bids rec'd 7-'55		

Note: Because of the remote location, these prices are about 7% above those closer to labor and material markets
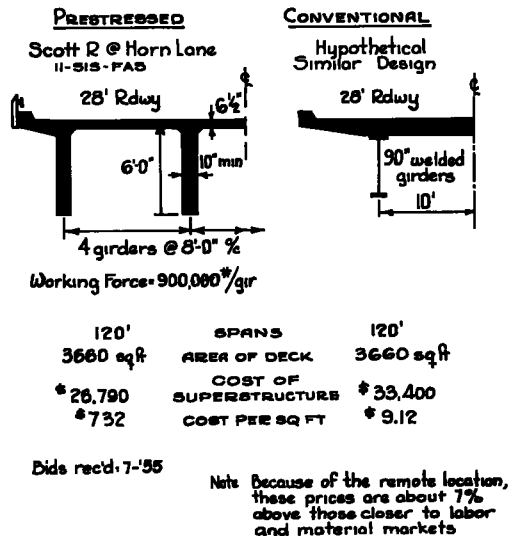
Figure 9.

two-span continuous, prestressing job. The prestressing wires were run through the open cells. The depth of girder was of prime importance and the use of prestressed concrete permitted the reductions of the depth to only 4 ft. The job was built in 1954 and, being the first continuous structure of this sort in this area, it is felt that the price was raised somewhat as a result of uncertainty as to what the job would require. Unit cost was $7.18 per sq ft.

The Sixth Street overcrossing built in 1952 gives a good comparison. Although the unit price of $5.07 is materially cheaper than the prestressed structure, it must be noted that the depth is also 2 ft greater. Also, this type of construction was being done very economically because

COMPARISON

PRESTRESSED — Harkness Ave POC IV-SF-68-SF

CONVENTIONAL — Buhman Ave POC VII-LA-166-A

Working Force = 1,230,000#

40', 58'6", 40' — SPANS — 2 @ 50'-8"
1779 sq ft — AREA OF DECK — 1656 sq ft
$5221. — COST OF SUPERSTRUCTURE — $5671.
$2.94 — COST PER SQ FT. — $3.42

Bids rec'd 5-'54   Bids rec'd 8-'52

Figure 10.

of the numbers of concrete box girders which had been built in the Los Angeles area. When a reduced headroom is essential, although more expensive in this case, it is possible to obtain it by the use of prestressed concrete. Future designs of this type should be considerably cheaper. The cost of the first bridge of a type is almost always relatively high.

Incidentally, on the John Street structure, difficulties during construction beset a contractor inexperienced in prestressing, and confirmed his apprehension. The fact that continuous spans are best stressed from both ends was not proved until a great deal of effort had been spent trying to stress from one end. The grouting operation proved very troublesome largely because of lack of know-how, and much delay resulted. These experiences became known and other contractors became wary. Higher prices were the inevitable result.

Figure 9 shows a deep, but thin, section T-beam bridge which was poured in place and then post-tensioned. The 6-ft deep girders worked out very economically for this 120 ft span. The unit cost was $7.32 per sq ft. It is estimated that this cost is about 7 percent higher because of the remote location of the structure.

No structure was available for comparison to the Scott River bridge, so a hypothetical design was made. Using two 90-in. welded girders with a similar span and width of roadway the unit cost was $9.12 per sq ft, showing a material benefit for the prestressed work.

Pedestrian Overcrossings

Figure 10 compares two pedestrian overhead structures. A pedestrian structure must be light and airy in appearance to be attractive. Prestressed concrete designs improve the appearance of pedestrian structures by making long, thin members feasible. The Harkness Avenue pedestrian overcrossing is a simple slab span 7 in. thick with two shallow side beams 13 in. deep. The deck is surmounted by a 6-ft steel railing made of parallel, vertical bars. The supports are wall-type bents 12 in. thick. The unit cost was $2.94 per sq ft.

The Buhman Avenue pedestrian overcrossing also strove for a light, thin appearance in conventional concrete design. However, it was necessary to make the edge beams 42 in. deep. The architectural treatment on the outside of the beam created a horizontal shadow breaking up the plain surface, and a low railing, similar to the Harkness Avenue structure, contributed to the open feeling. Neither from the standpoint of appearance nor from that of cost ($3.42 per sq ft) did the conventional structure approach the clean open lines of the prestressed design.

Conclusion

Prestressed concrete is not a cure-all, and it is not applicable to all situations. It
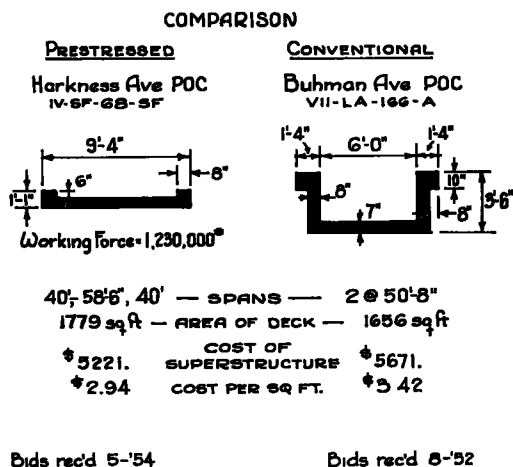
has certain advantages which may give benefits not reflected in unit costs. It permits the construction of long beams which may be lifted into place without the necessity for falsework or for interruption of traffic beneath a structure. It permits more slender and shallow members, allowing greater headroom and decreasing the required depth of a structure. It permits a member to be built in place and then post-tensioned to take its share of the load. When pretensioned, it permits members to be built economically in yards and hauled to the structure site.

It has little advantage on very short spans. It raises the difficulty of tying together precast concrete members. It calls for precision of workmanship beyond that usually found in concrete construction. It requires specialized knowledge and special techniques and equipment. It demands a certain amount of experience and know-how. This last reason has been outstanding in holding construction prices higher than warranted.

Prestressed concrete is a new medium with definite uses. Cost alone is not the entire answer, and cost of prestressed work will decrease with time and experience. In the future, prestressed and precast beams will be bought on the market as a standard stock item. An amalgamation of the various prestressing systems to promote prestressed concrete as a whole and to subdue detrimental competition is probable. The position of prestressed concrete in the construction field will be clarified by these factors.

The time will soon come when the engineer who considers the use of prestressed concrete will find that, for the benefits derived and for the money expended, prestressed concrete adds a new, economical, and exciting medium to the many which the structural engineer may use.

ACKNOWLEDGMENT

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUN-
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ACADEMY itself was established in 1863 under a congressional charter
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