Segmental Concrete Arches on the Natchez Trace Parkway

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Today's design and construction of major highway structures is increasingly becoming a "high tech" field for the structural engineer. These bridges are considered to be "high tech" because of the complex mathematical process that is required for their design and construction/erection. Designs such as these are only accomplished through the use of very complex computer-based design programs. The need for engineers to be capable of designing and constructing such structures is due in part by the need of the local community and the nation to get the most from the available highway dollar. Today's project requirements relative to environmental concerns such as wetlands and water quality also drive the demand for the design of longer span bridges with sophisticated erection schemes. Consequently, the engineering community is using more and more segmental concrete design and construction methods as a means to addressing these concerns. A segmental concrete arch bridge to carry the Natchez Trace Parkway over Tennessee Route 96 near Franklin, Tennessee, is such a structure.

BACKGROUND

The Natchez Trace Parkway is a two-lane roadway owned and maintained by the National Park Service which takes park visitors from Nashville, Tennessee, to Natchez, Mississippi, along an alinement that follows very closely the original Natchez Trace. The trace was first probably a series of hunters' paths that slowly came to form a trail from the Mississippi over the low hills into the valley of the Tennessee. As early as 1733, the French were familiar enough with the land to make a map that showed an Indian trail running from Natchez to the northeast. By 1785, American settlers in the Ohio River Valley had established farms and, in search for markets, had begun floating their crops and products down the rivers to Natchez or New Orleans. Returning home meant either riding or walking, for the flatboats, too, were sold for their lumber, and the trail from Natchez was the most direct route home. As the numbers of boatmen grew, the crude trail was tramped into a clearly marked path. Over the years, improvements were made, and by 1810 the trace was an important wilderness road, the most heavily travelled in the Old Southwest. Even as the road was being improved, other comforts, relatively speaking, were coming to the trace. During these years, many inns--locally called stands--were built. By 1920 more than 20 stands were in operation. Most of them provided no more than a roof over one's head and plain food. But even with these developments, the trace was not free of discomforts. Gangs of thieves added an element of danger that was only one more hazard in a catalog that included swamps, floods, disease-carrying insects, and unfriendly Indians.

Since the late 1930's, the National Park Service has been constructing a modern parkway that closely follows the course of the original trace and gives the present-day traveller an unhurried route from Natchez to Nashville. The construction of a structure which will carry the Natchez Trace Parkway over Tennessee Route 96 is one more link toward the final completion of the Parkway. The crossing is such that the parkway grade is approximately 155 feet in elevation above Tennessee Route 96. The north side of the crossing contains a tree-covered bluff that will be undisturbed during the construction of the bridge. In keeping with the history of the trace and desire by the National Park Service to have a structure at this crossing that will blend in with the surrounding terrain, an arch-type structure was selected.

STRUCTURE DESCRIPTION

The bridge is 1,648 feet in length with a main arch span of 582 feet, as shown in Figure 1. The superstructure, which is a post-tensioned concrete box section, rests on the arch section and is not a part of the arch construction as is done in most arch bridges. This is done to prevent the thermal effects of the arch from producing secondary forces in the main superstructure elements.

The superstructure is composed of span lengths from abutment 1 to abutment 2 (north to south) of 204' - 246' - 90' - 246' - 246' - 90' - 246' - 204'. The remaining bridge length is composed of 38-foot concrete tee-beam spans as part of the cast-in-place decked-over abutments. The two 90-foot spans are located on the top of each arch span. The 246-foot end spans then close the gap from the pier to the crown of the arch. The bridge is designed to be built as either a cast-in-place or precast, segmental concrete structure. Both designs use the same geometry and structural element sizes. That is, each construction type will produce identical finished structures.

CAST-IN-PLACE SEGMENTAL DESIGN

Foundation

All substructure units are to be founded in a rock layer locally known as Brassfield limestone. Preliminary field borings indicated that the limestone was located about 30 feet below the existing ground surface. At the base of the slope for abutment 1, the location of pier 1 and thrust block 1, preliminary foundation data indicated the possibility of cavities in the limestone formation. Since the footing for pier 1 is a thrust block, both vertical and horizontal forces have to be accounted for in the foundation design. Excavating for the foundation of pier 1 during construction and encountering a

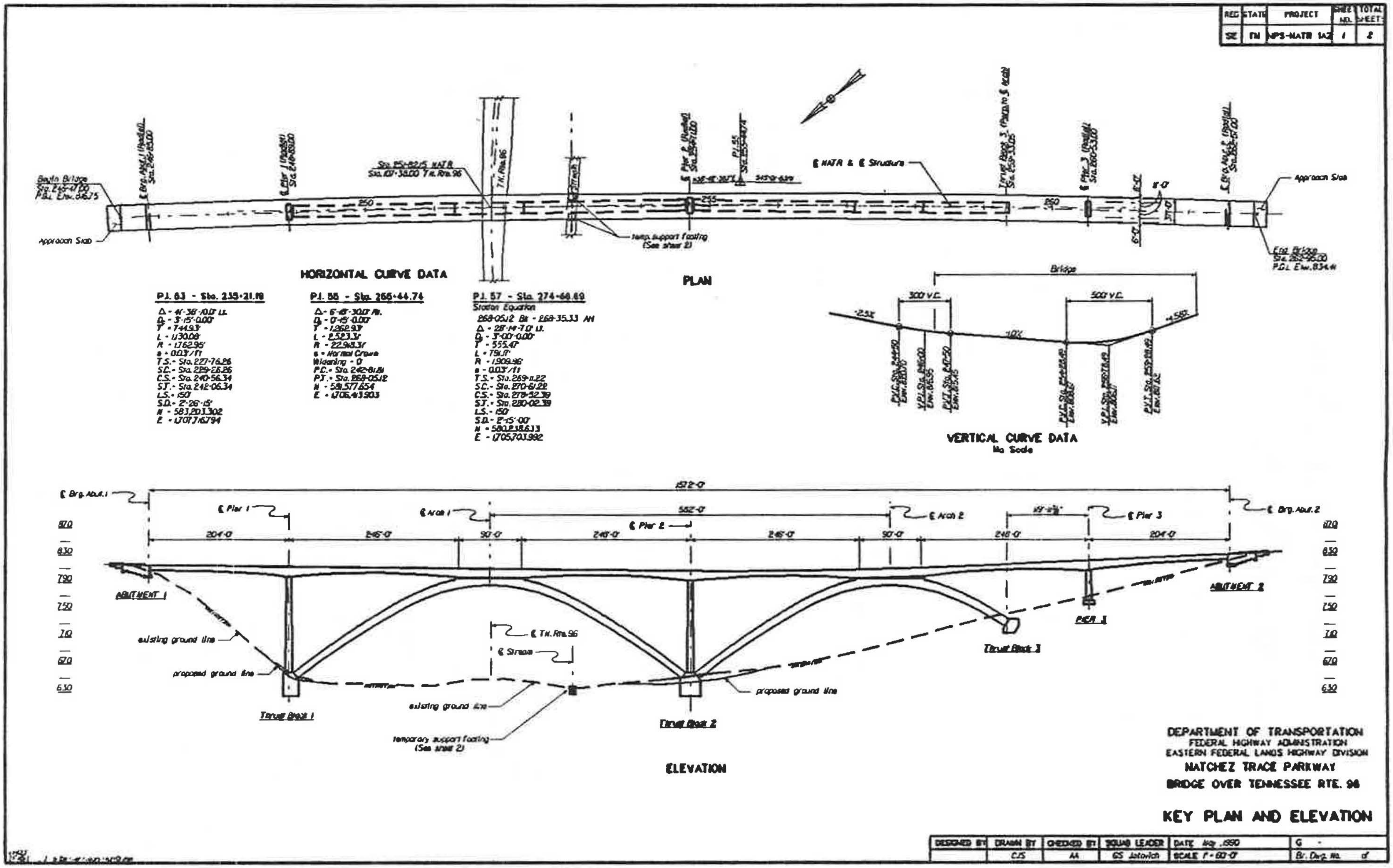

FIGURE 1 Bridge plan and elevation view

large cavity was not considered a desirable way to start work on a major bridge structure.

In order to thoroughly investigate the foundation for pier 1, two choices were considered. One choice was to drill the area with boreholes on about a 5-foot grid. Due to the size of the foundation, this was considered to be very expensive and time consuming. It also did not preclude the possibility of not locating a cavity. This was an unacceptable deficiency with this type of investigation.

The second choice and ultimately the method of investigation used was Crosshole Seismic Scanning and Tomography. This is a method of foundation investigation where boreholes are placed around the periphery of the footing, a thrust block in this case. Sensors are then placed in all but one borehole. The remaining borehole contains a seismic wave-generating device. By incrementally positioning these units in the boreholes, the entire foundation area is mapped by measuring the seismic velocity and wave attenuation between the seismic generator and the receiver. While the process of crosshole seismic scanning is not new, the ability to use this data along with a computer program to develop a tomographic image of the foundation material is gaining widespread use. Figure 2 is a sample of the tomographic image that is developed using this process. The dark area on the image is the cavity. By using multiple two-dimensional images developed between the seismic generator and the receivers, a three-dimensional map of the area can be developed showing the limits of any cavities.

Piers

The piers are designed as single-cell concrete box segments to be built using the cast-in-place slip forming method. The inside of the pier contains a ladder and landing system for future inspection. The pier heights range from a maximum of about 140 feet to a minimum of 43 feet. The piers are tapered in both directions with the taper for all piers being identical. The taper is set by pier 1, which is the tallest. Pier caps are 7 feet by 15 feet 6 inches. The base dimension for pier 1 is 10 feet by 22 feet.

Arches

The structure contains two arch supports. The main arch span is a symmetrical span of 582 feet and crosses Tennessee Route 96. The arch segment is to be constructed as a single-cell concrete box section. The inside of each cell contains a metal staircase ladder for future inspection. The second arch contains the same geometry as the main arch span but is only about 80 percent of the main arch. This is because the terrain beneath this span is sloping upward from pier 2 to pier 3. Consequently, the support for the second half of this arch does not coincide with the base of pier 3. This support base is located in the slope about 120 feet from pier 3 toward pier 2.

The arch geometry is a series of compound circular arcs along the intrados of the arch. This type of geometry was chosen so that minimal flexural stresses would be present in the legs of the arch. This is desirable in the design of each arch since the arch contains no spandrels. Each arch is also designed on an offset tangent horizontal alinement since the superstructure is on a 0° - 15' horizontal curve. This requires that the arch base and the pier base be offset by about 1 foot 4 inches.

The cast-in-place design requires that the arch be constructed in about 90-foot long segments using temporary tower support piers and a reusable support truss, as shown in Figures 3 and 4. As each section is built, the support truss is unloaded and moved to the next segment to be constructed. The completed arch segment then supports itself between each support or about every 90 feet. The arch is constructed simultaneously from both ends with the top or crown being cast last. All but the very crown and base of the arch is constructed using mild reinforcement. The crown and base of the arch contain post-tensioning reinforcement in addition to mild reinforcement due to the flexural stresses in the arch caused by the reactions of the 246-foot adjacent superstructure spans on the crown of the arch.

Superstructure

The superstructure for this structure is a single-cell concrete box with 8-foot-6-inch cantilevers supporting a concrete and aluminum bridge rail. The roadway carries two 11-foot traffic lanes with 6-foot shoulders. The railing width is 1 foot 6 inches, which gives an overall superstructure width of 37 feet out-to-out. The superstructure varies in depth from 14 feet at the piers to 7 feet 6 inches at the abutments and centerlines of each span. The section is a constant 12-foot 11 1/4-inch depth for the 90-foot span at the crown of the arch. The sides of the box are on about a 2 to 12 slope which gives the bottom of the box a varying width of about 17 feet 10 inches to 15 feet 4 inches. The superstructure contains both longitudinal post-tensioning in the webs and transverse post-tensioning in the deck.

The superstructure is designed to use the same temporary support tower piers used for the arch construction with a reusable truss support system, as shown in Figures 5 through 11. The 90-foot segment at the crown of the arch is cast using the arch as support. The abutment 2 end span is built using typical ground-based falsework as support. The end span at abutment 1 is built using an inverted Queenpost truss. This is done to keep from disturbing the fragile slope between abutment 1 and pier 1.

Abutments

After the main portions of the bridge are constructed, the 38-foot long decked-over abutments will be completed. The entire structure will finally receive a 1 1/4-inch thick latex modified concrete overlay as a final wearing surface. All exposed vertical faces of the structure and the concrete portion of the bridge rail will receive a hand-rubbed concrete finish. The abutment wings are to be faced with local stone.

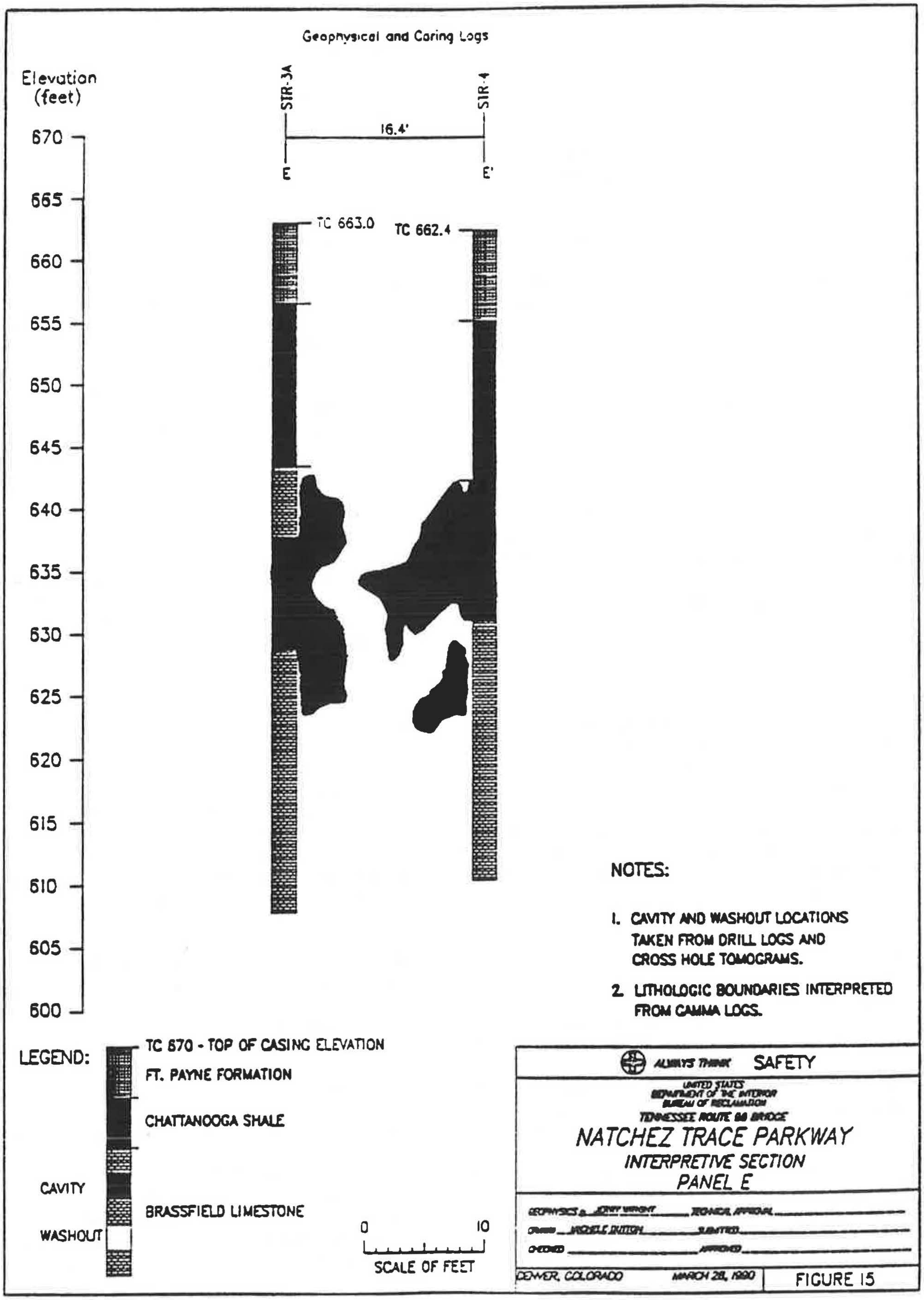

FIGURE 2 Tomographic image of cavities in limestone (dark area denotes cavity)

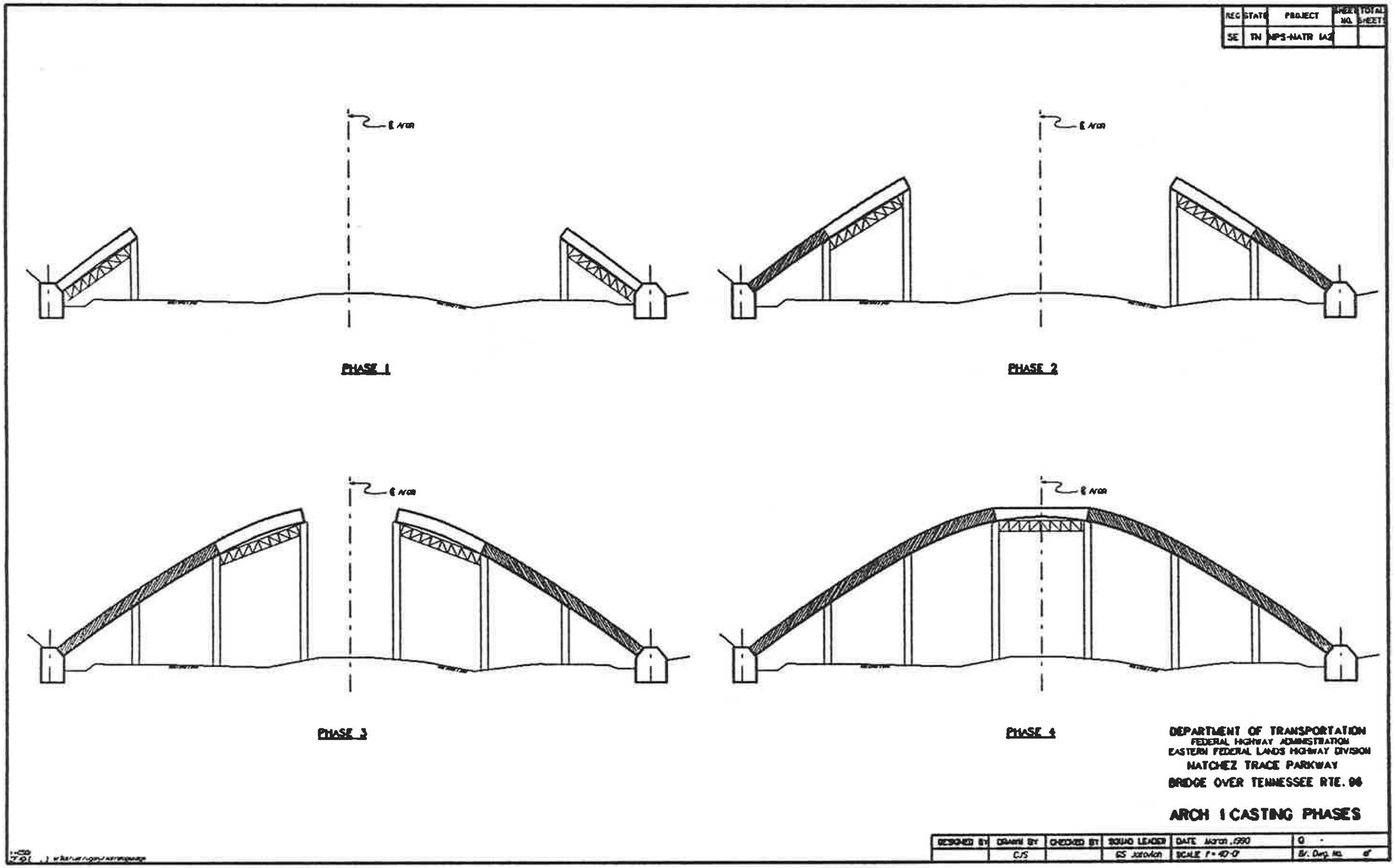

FIGURE 3 Arch 1 erection sequence

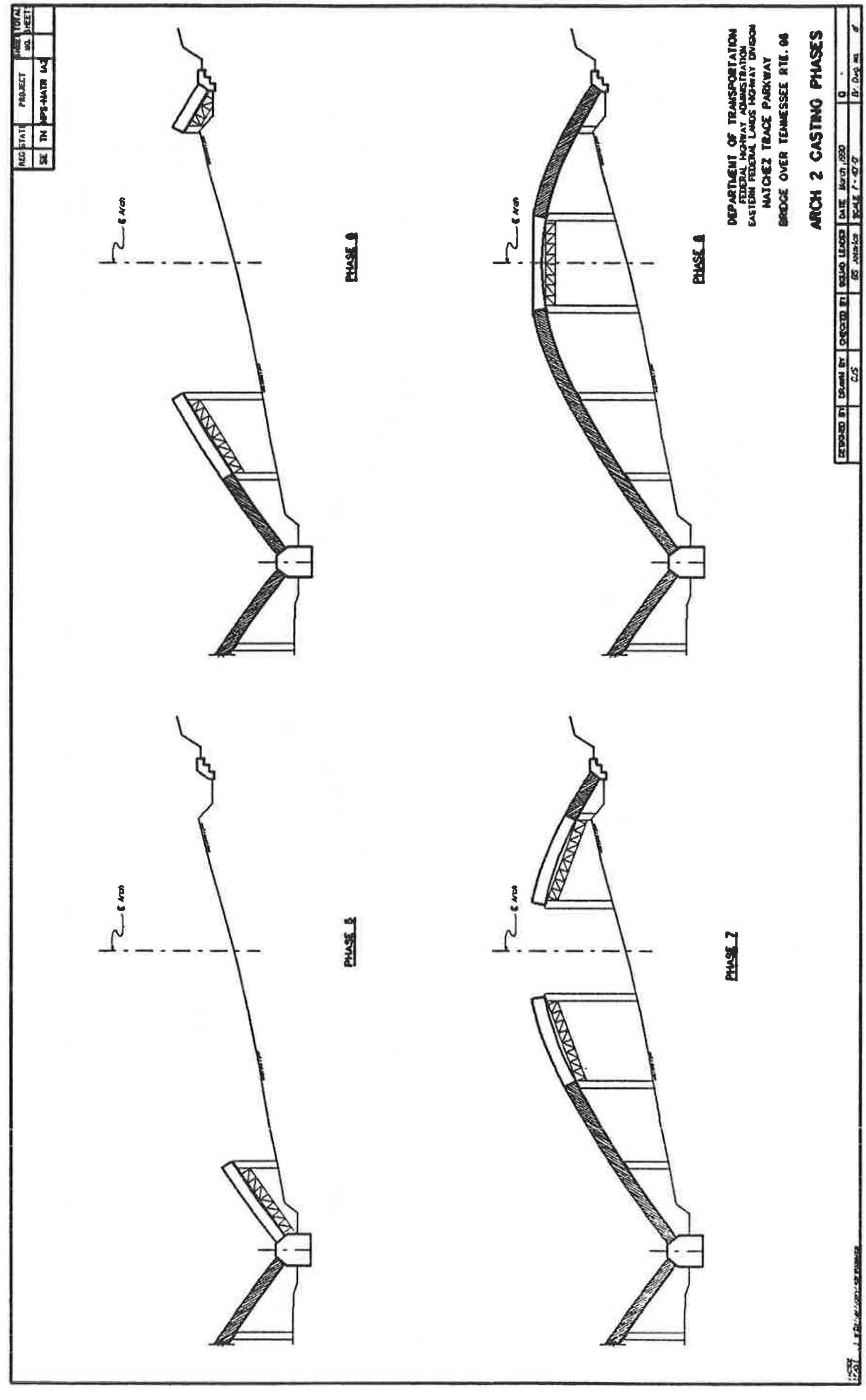

FIGURE 4 Arch 2 erection sequence

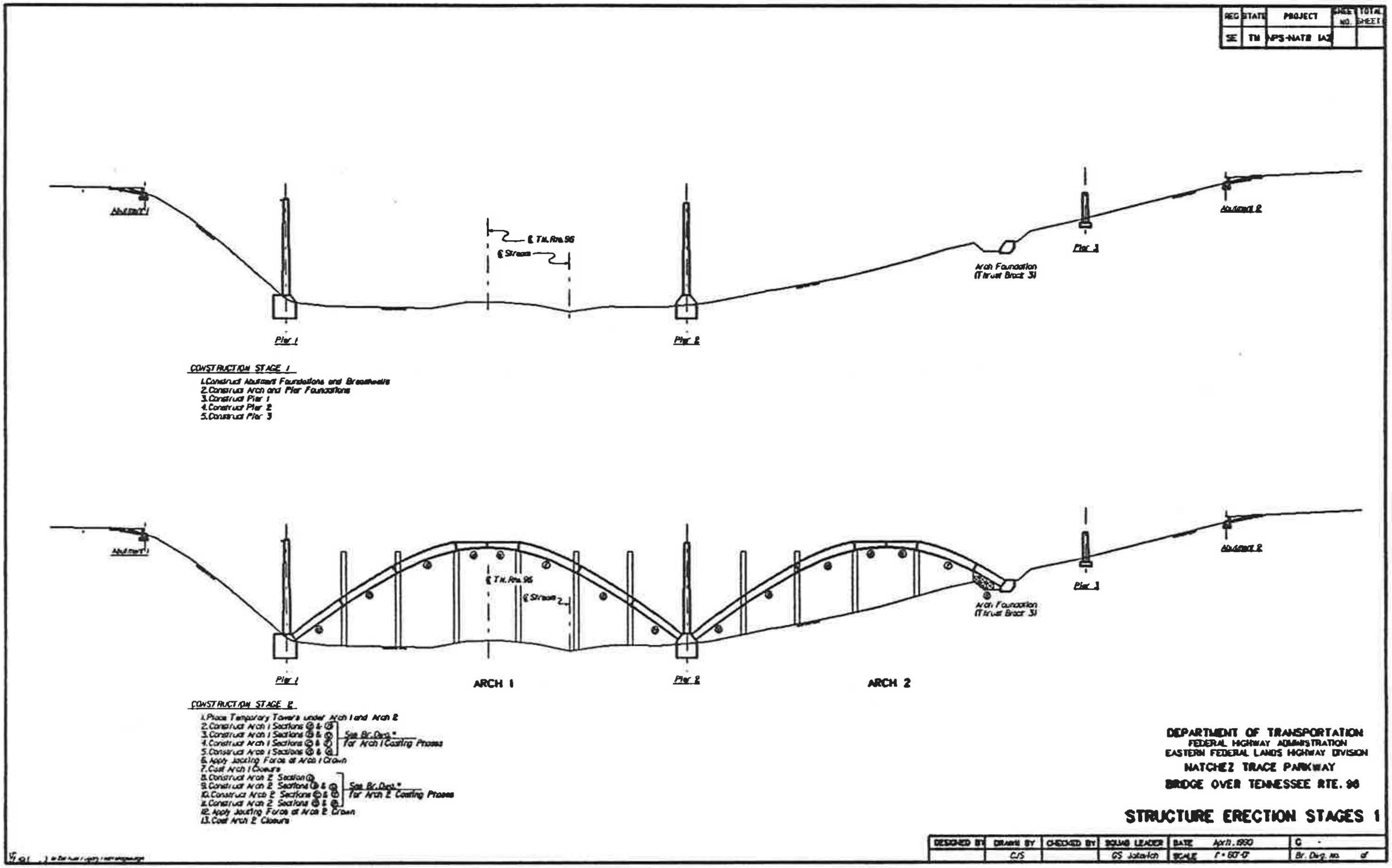

FIGURE 5 Construction stages 1 and 2 showing substructure construction

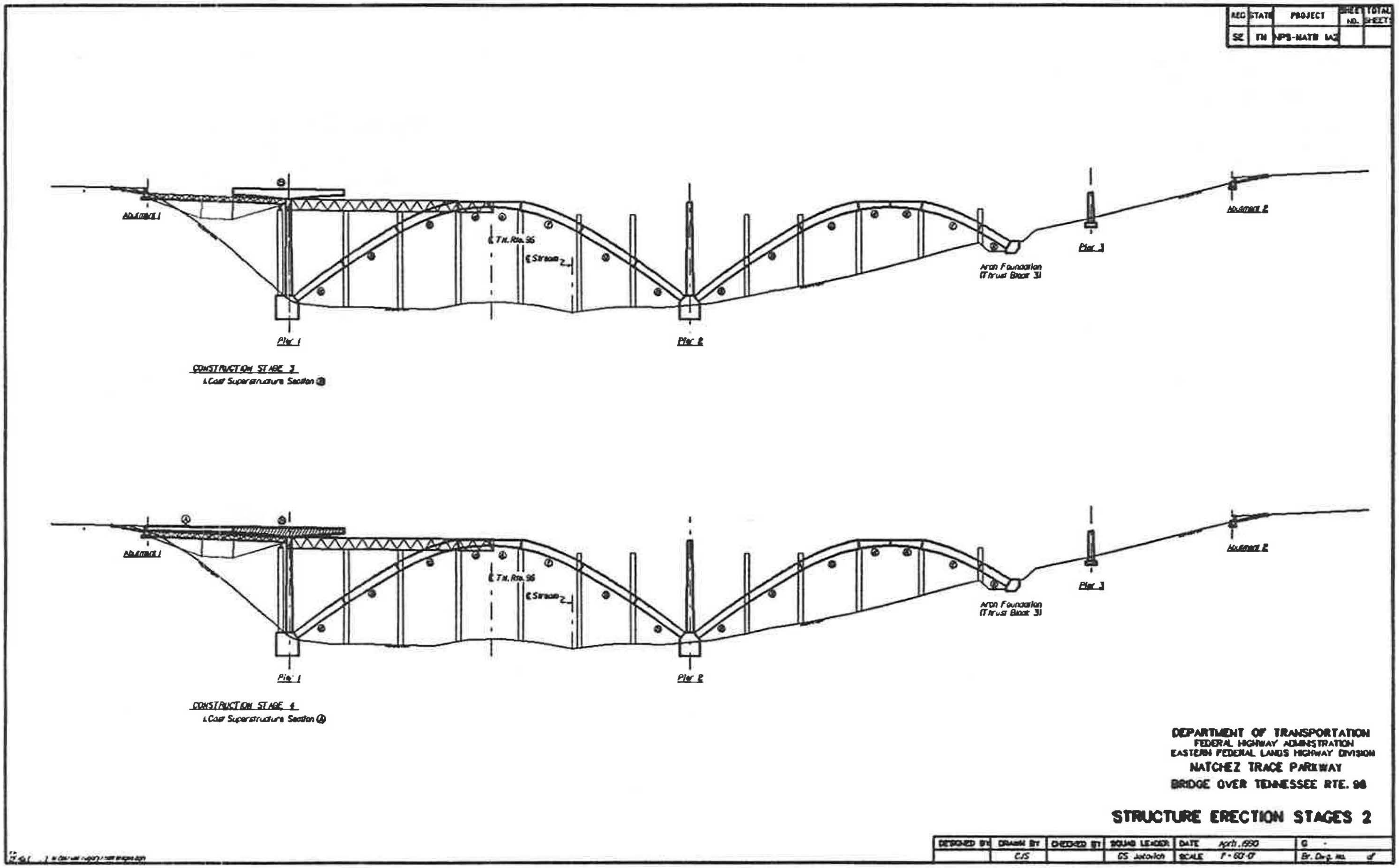

FIGURE 6 Construction stages 3 and 4 showing span 1 and span 2 cantilever placement

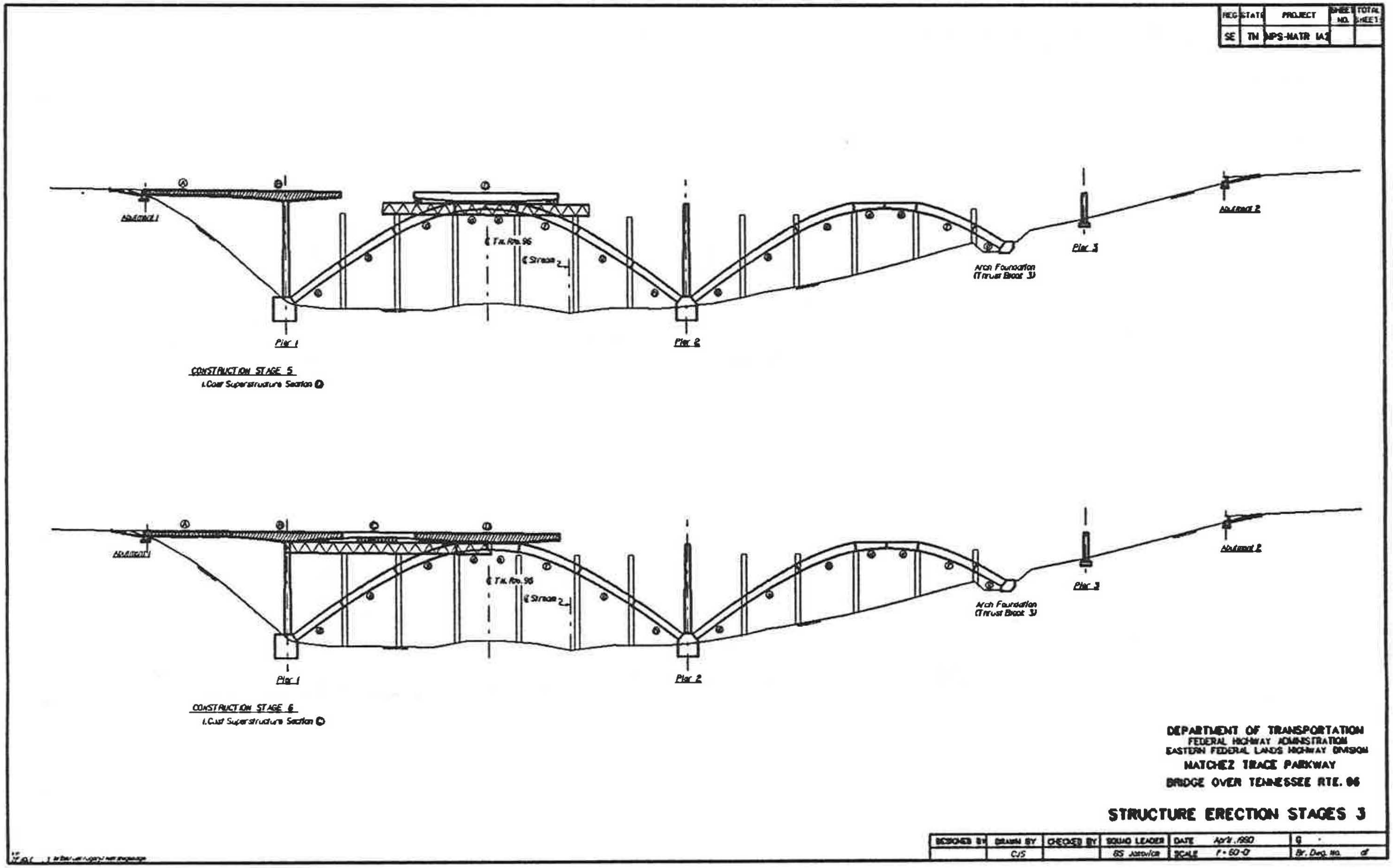

FIGURE 7 Construction stages 5 and 6 showing arch 1 (span 3) cantilever and span 2 closure placement

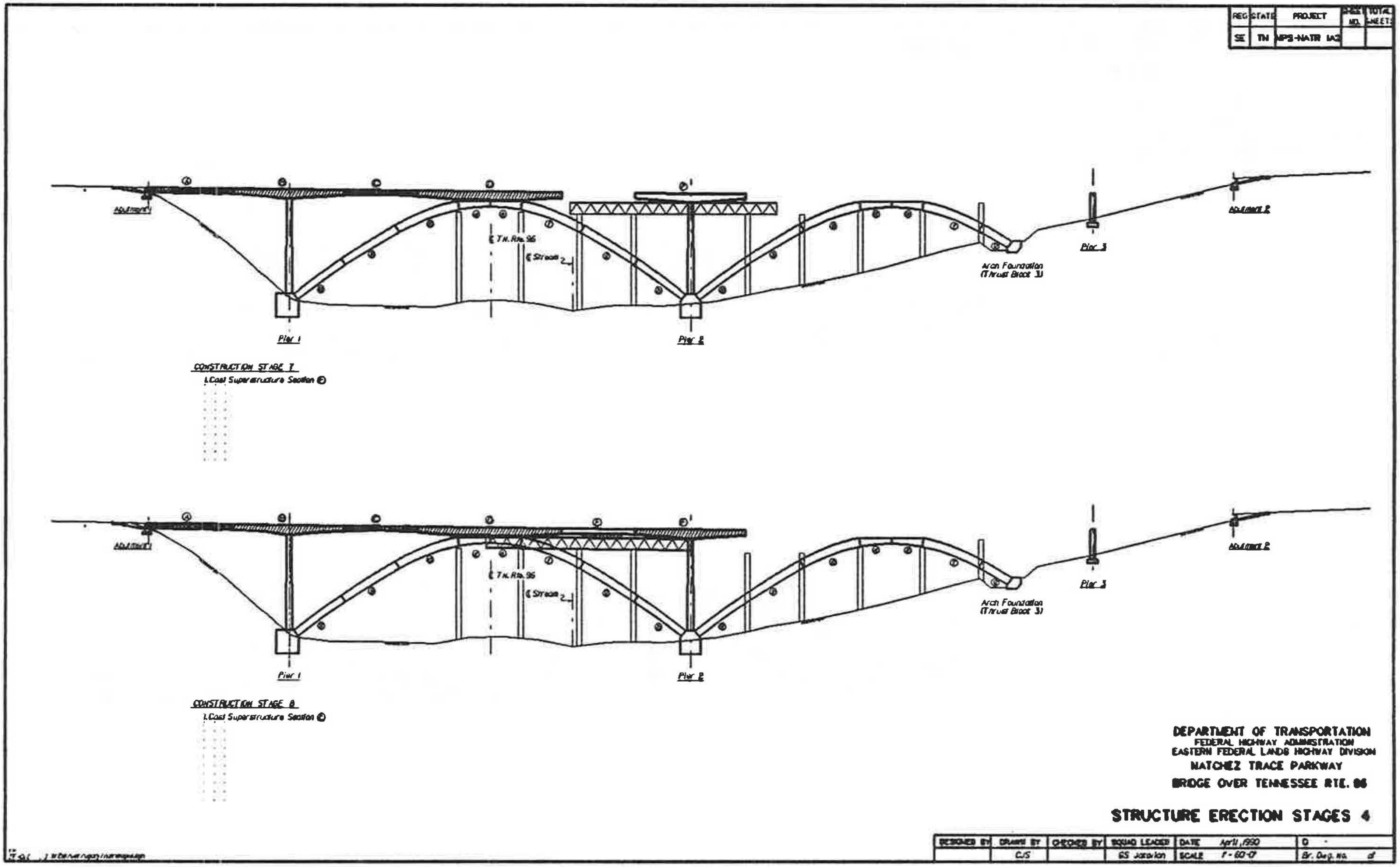

FIGURE 8 Construction stages 7 and 8 showing pier 2 cantilever and span 4 closure placement

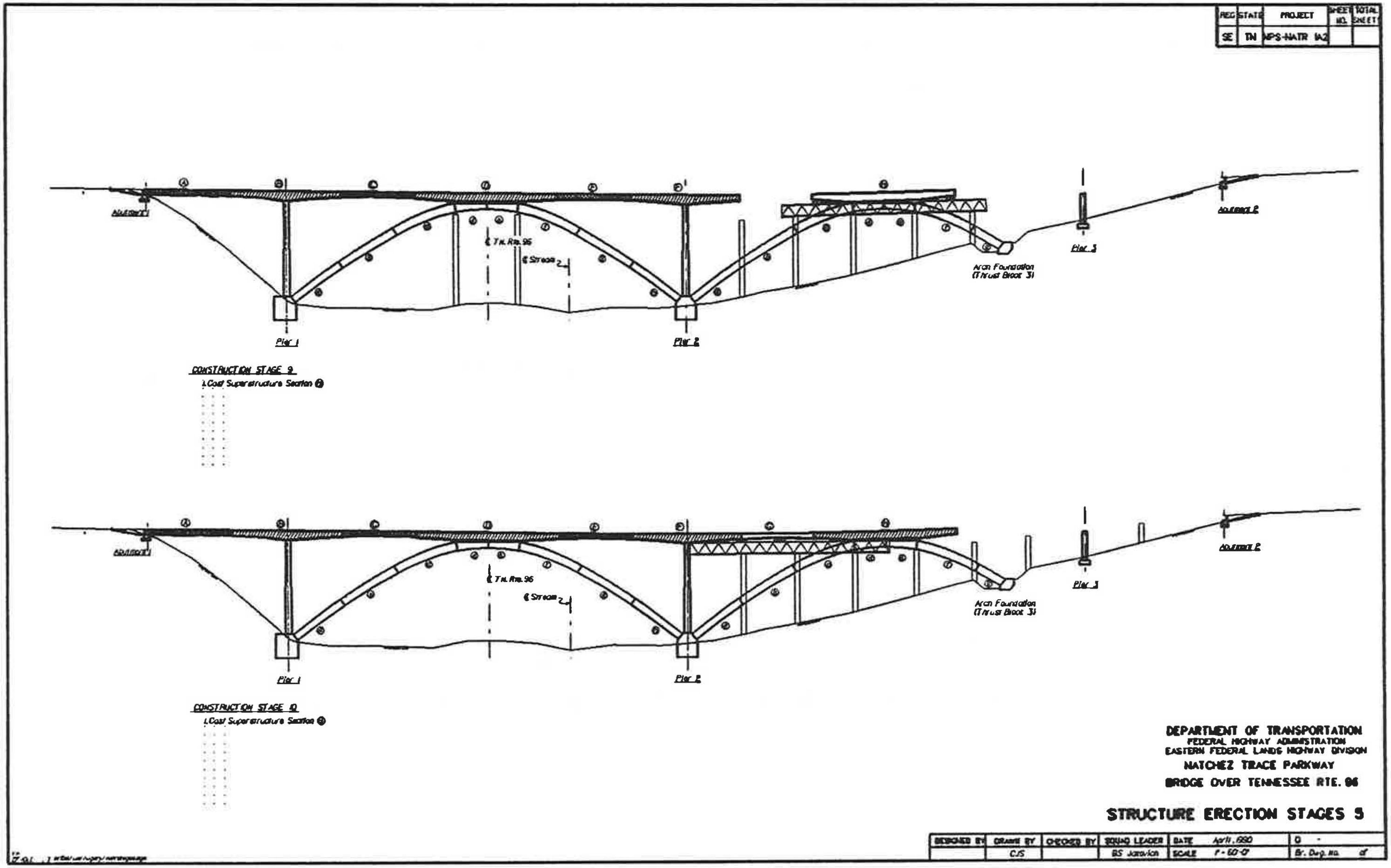

FIGURE 9 Construction stages 9 and 10 showing arch 2 (span 6) cantilever and span 5 closure placement

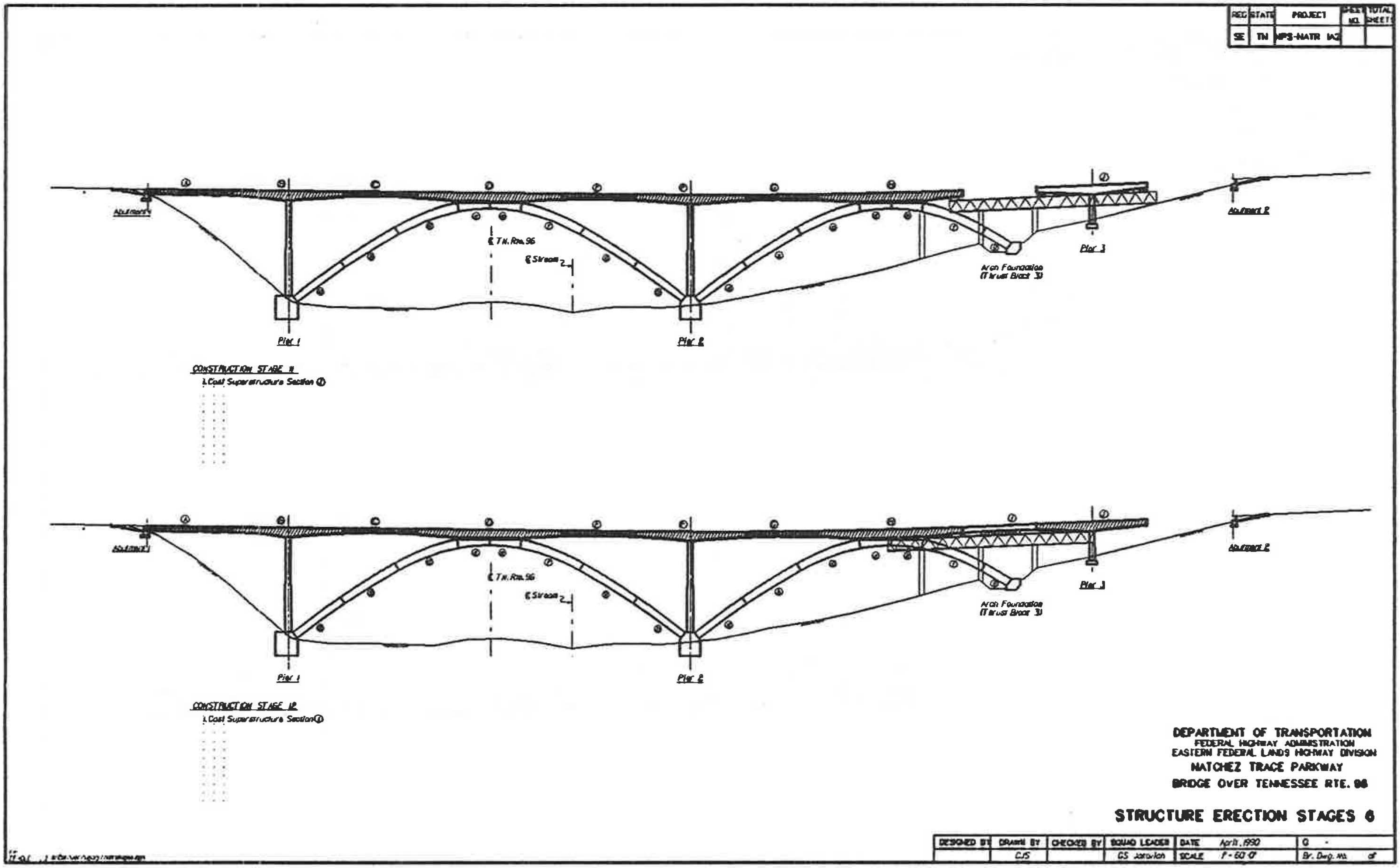

FIGURE 10 Construction stages 11 and 12 showing pier 3 cantilever and span 7 closure placement

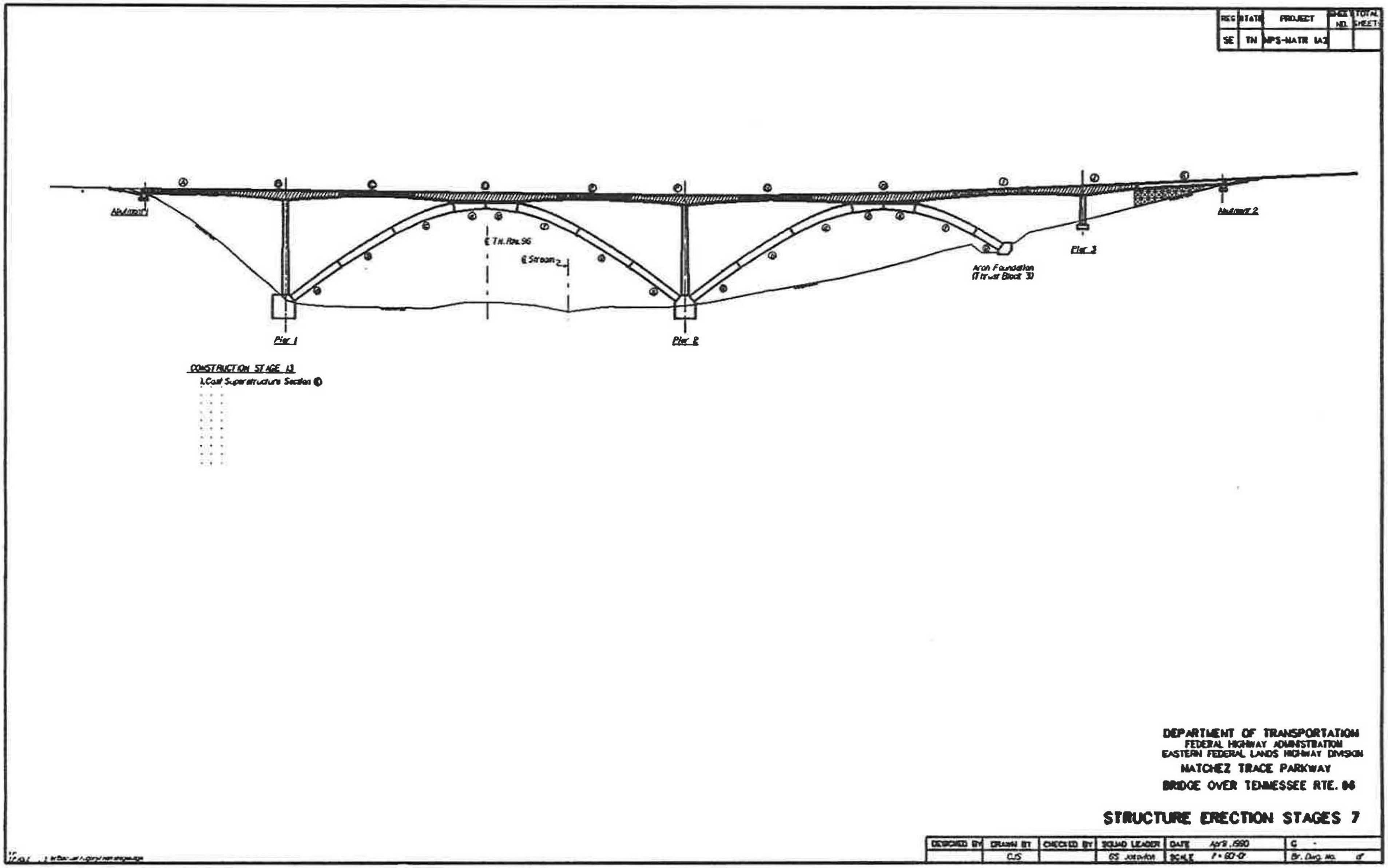

FIGURE 11 Construction stage 13 showing span 8 closure placement

PRECAST SEGMENTAL DESIGN

A second design and construction/erection method proposed for this structure, except for the foundations, uses precast segmental techniques. The piers, arches, and bridge superstructure are made of precast segments erected by either the span-by-span or balanced cantilever methods of construction. This approach represents the first use of precast segmental technology for an arch bridge in the United States. All major features of the precast segmental design are the same as the cast-in-place design.

Foundations

As previously mentioned, only the foundations for this design are constructed with cast-in-place concrete. These elements are abutments 1 and 2, thrust blocks 1, 2, and 3, and pier 3 footing. Each of these bear directly on the underlying rock stratum without the aid of piles or drilled shafts. The material encountered at the site at bearing level is mainly limestone with permissible bearing pressures between 14 and 24 tsf.

Thrust blocks 1, 2, and 3 are cast-in-situ concrete placed after excavation to acceptable bearing material. Ductwork and anchorages for the post-tensioning of the precast arch and pier segments are embedded in the thrust blocks. The quantity of concrete in the thrust blocks are 980, 870, and 490 cubic yards for thrust blocks 1, 2, and 3, respectively.

Piers

The three piers of the project are precast, segmental box piers. The tapers were established by setting the dimensions of the base of the tallest pier (pier 1). These dimensions are 10 feet longitudinally and 22 feet transversely. With the taper set, the variable segment dimensions are determined. The base dimensions of piers 2 and 3 are, therefore, a function of their height. Selecting dimensions in this fashion produces similar precast segments at the same relative elevation from the top of the piers.

The precast box pier segments are typically 10 feet in length. The maximum weight is 45 tons and the minimum weight is 33 tons. The pier caps are solid precast segments 7 feet by 15 feet 6 inches by 3 feet 9 inches and weigh 31 tons.

The precast segments are vertically post-tensioned with a combination of post-tensioning bars and strand tendons. Four 1 3/8-inch diameter high strength post-tensioning bars are typically placed between the precast segments. This number is increased to 10 bars for the last four segments of the taller piers. Two 19 by 0.6-inch diameter strand tendons are placed U-shaped through the pier foundation for the full height of the pier. All joints in the precast piers are joined with epoxy.

Arches

In plan view the roadway alinement follows a 0° - 15' curve over the entire length of the project. To accommodate this curvature, the arches are held straight and placed on chords which pass through the arch superstructure bearings. This results in an angle break between the lines of action of the arch thrusts at pier 2 and offsets between the centerlines of piers and the arch thrust lines at piers 1 and 2. Thrust block 3 is located independently of pier 3 as previously described.

The profile of the arches is a series of compound circular arcs on the intrados. The radii vary from 1,150 feet at the base to 240 feet at the crown. The thickness of the arches vary from 10 feet at the base to 13 feet at the centerline of bearing of the superstructure (45 feet off of centerline of arch). The arches then vary back to a depth of 10 feet at their centerline. These variations to establish the extrados are linear with length along the intrados.

The width of the arches is 16 feet 1 inch. The cross section is a single-cell box girder with 1 foot-thick walls. The maximum segment weight is 45 tons and the minimum weight is 29 tons. The typical length of the arch segments is 10 feet and a total of 68 segments are used to construct arch 1, and 54 segments are used in arch 2.

The erection procedure of the arches innovatively uses the span-by-span method of construction, as shown in Figures 12 through 18. This method was developed over 12 years ago for the erection of the Long Key Bridge in the Florida Keys. Since then numerous precast segmental superstructures have been assembled using this method and many refinements have been made. The span-by-span erection of the arches will demonstrate a new application of this efficient method of construction.

To build the 582-foot span arch (arch 1) along its chord, seven intermediate "spans" between 80 and 90 feet are established. These intermediate "spans" are supported by temporary piers which may be reused for the construction of arch 2. Construction begins at thrust block 1 (pier 1). Temporary pier 1 is erected and assembly trusses are positioned in the first intermediate span. Segment 1 is placed on the assembly trusses and stressed back to thrust block 1. In repeating fashion, each of the remaining first nine precast arch segments are epoxyed and stressed together. Typically, 10 1-3/8-inch diameter high strength bars are used to stress the precast arch segments together. Eight additional bars are used near thrust block 1 to help control flexural stresses. When all of the segments of this span are erected, the assembly trusses are lowered and the segments span between thrust block 1 and the first temporary pier.

Construction continues with the assembly of segments 10 through 19 and segments 20 through 29 in intermediate spans 2 and 3, respectively. Once these three spans are complete, the assembly trusses are moved to span seven adjacent to thrust block 2. Spans 5 through 7 are then assembled in reverse order which, when complete, produce two three-span structures symmetrical about the centerline of the arch.

In the last phase of construction of this arch, the assembly trusses are positioned in the fourth or central intermediate span. Segments 30 through 34 are epoxyed and stressed to the left three-span structure while segments 35 through 39 are assembled to the right three-span structure, leaving a 1-foot closure joint at the arch centerline. Hydraulic jacks are then positioned in the closure joint and the two arch halves are jacked apart with a force of 1,000 kips. The closure joint is then poured and after minimum compressive strength isreached four 19-inch by 0.6-inch diameter post-tensioning tendons per web are stressed completing the arch.

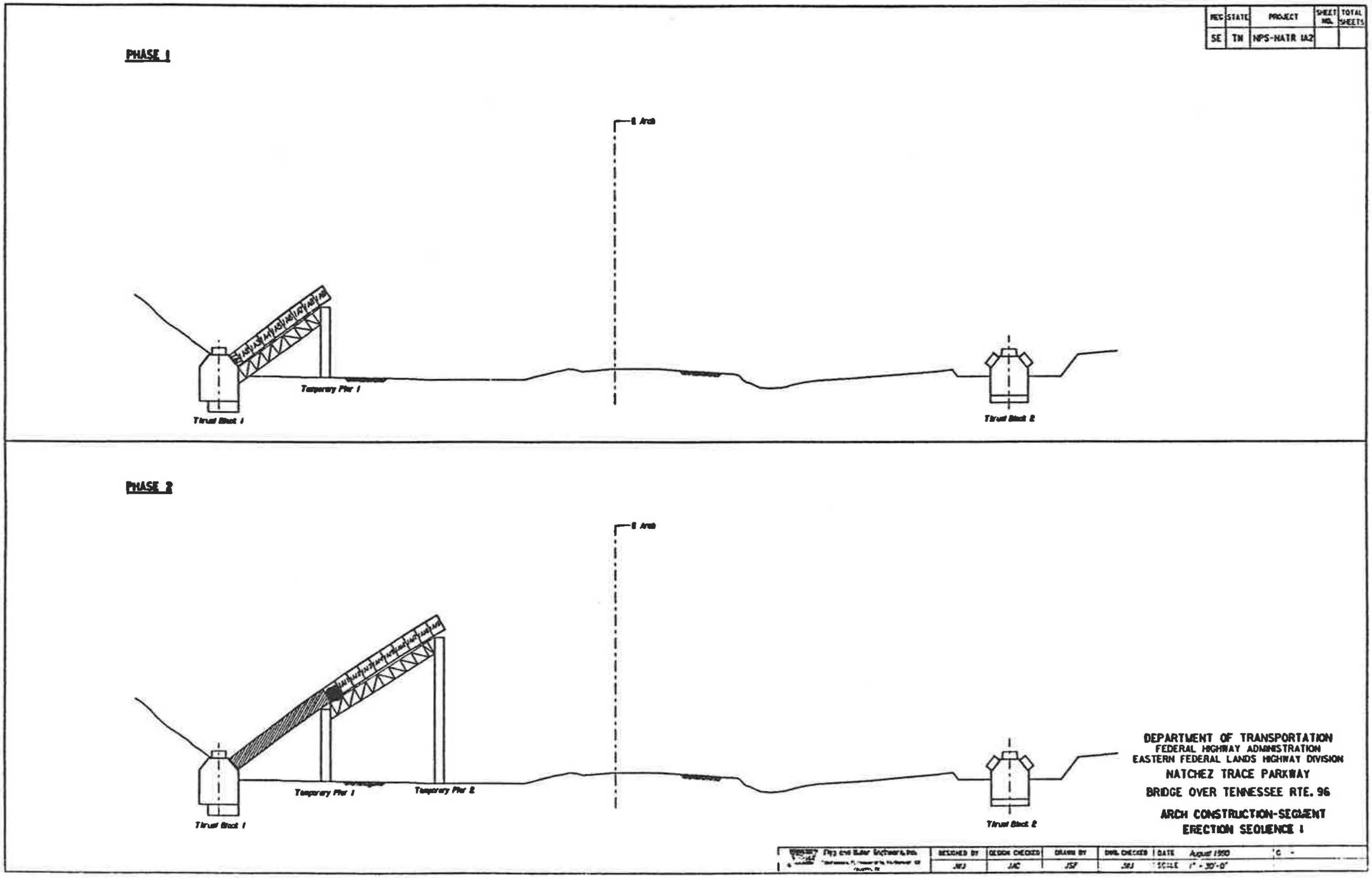

FIGURE 12 Arch construction - precast alternate - phases 1 and 2

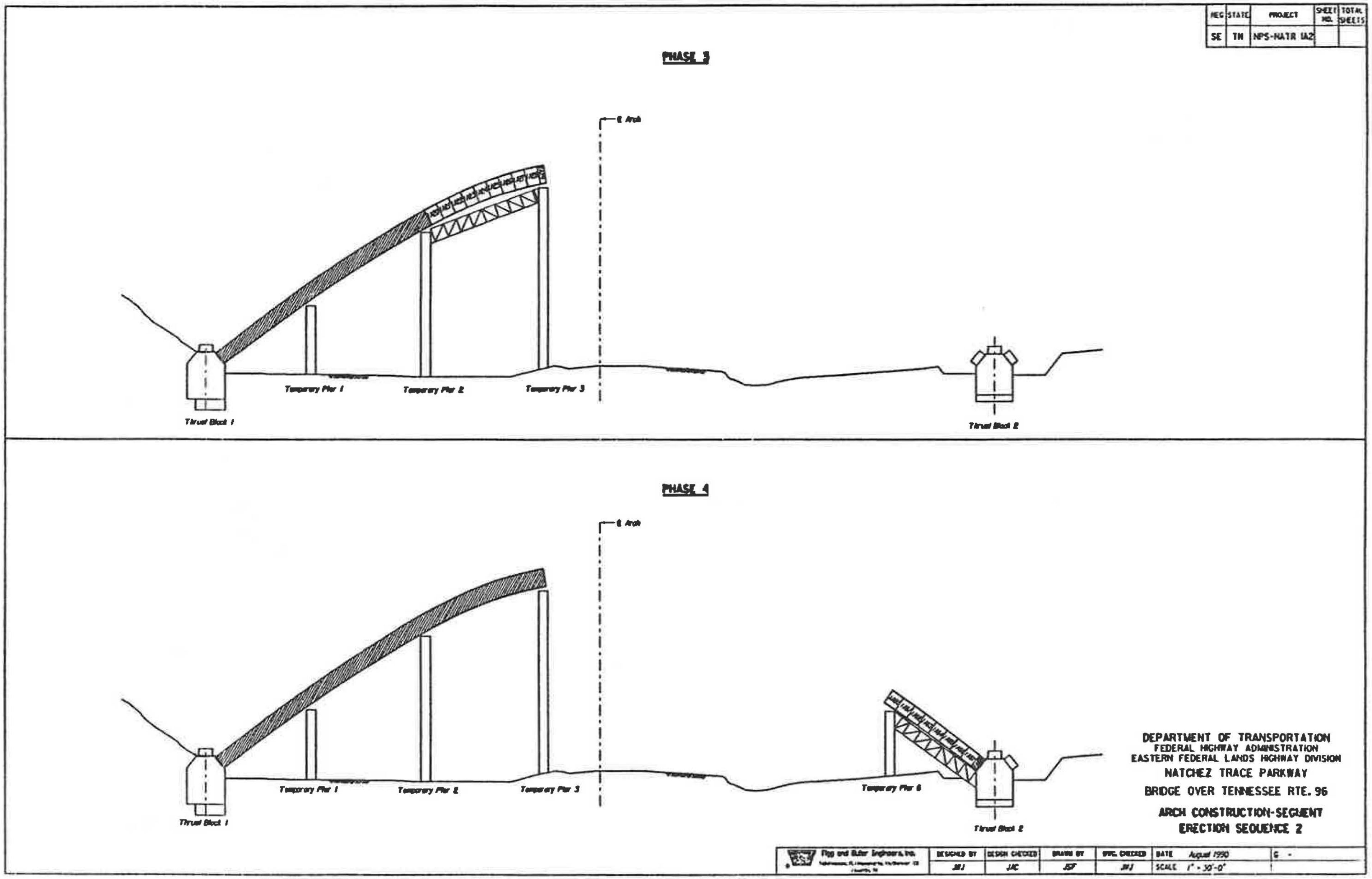

FIGURE 13 Arch construction - precast alternate - phases 3 and 4

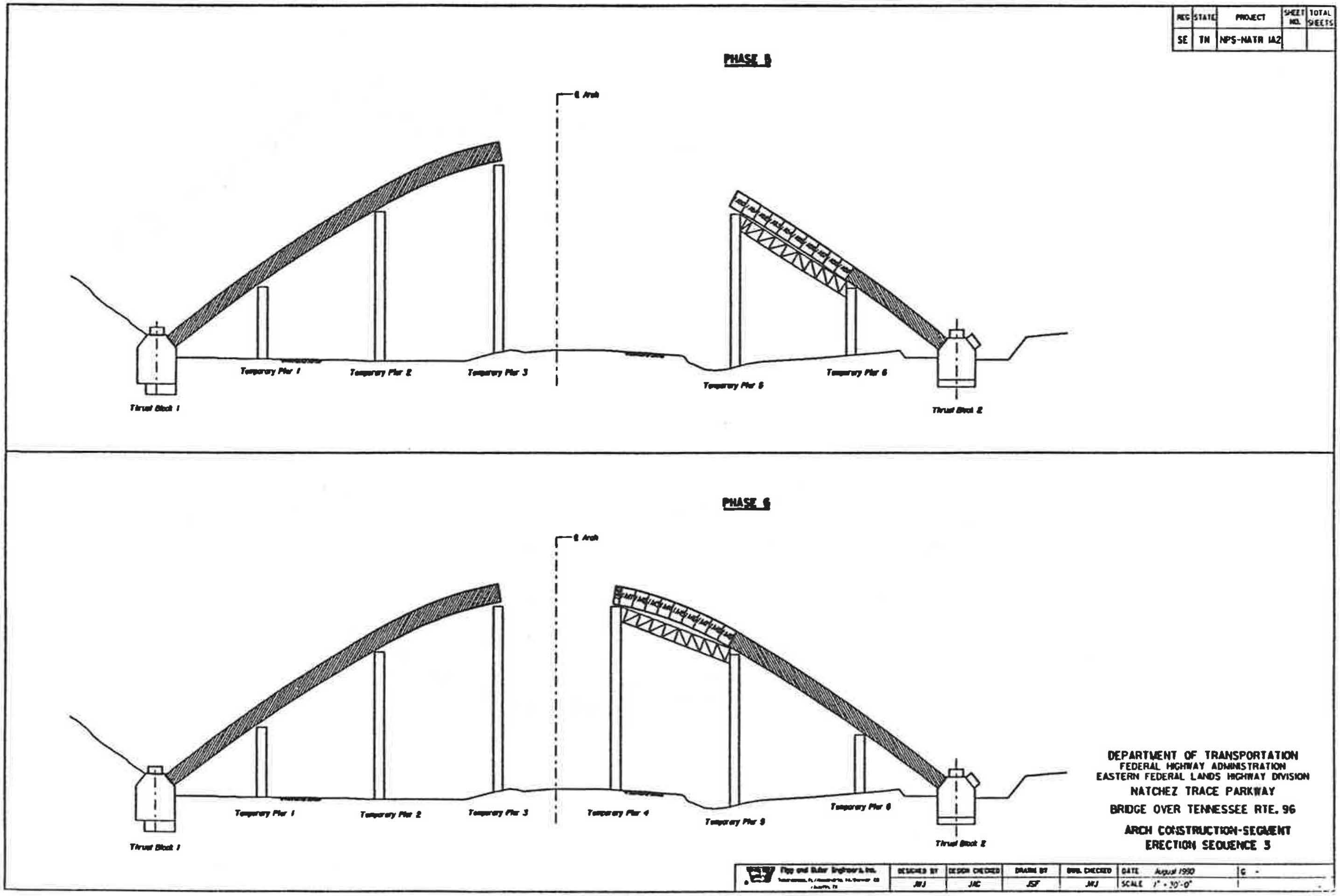

FIGURE 14 Arch construction - precast alternate - phases 5 and 6

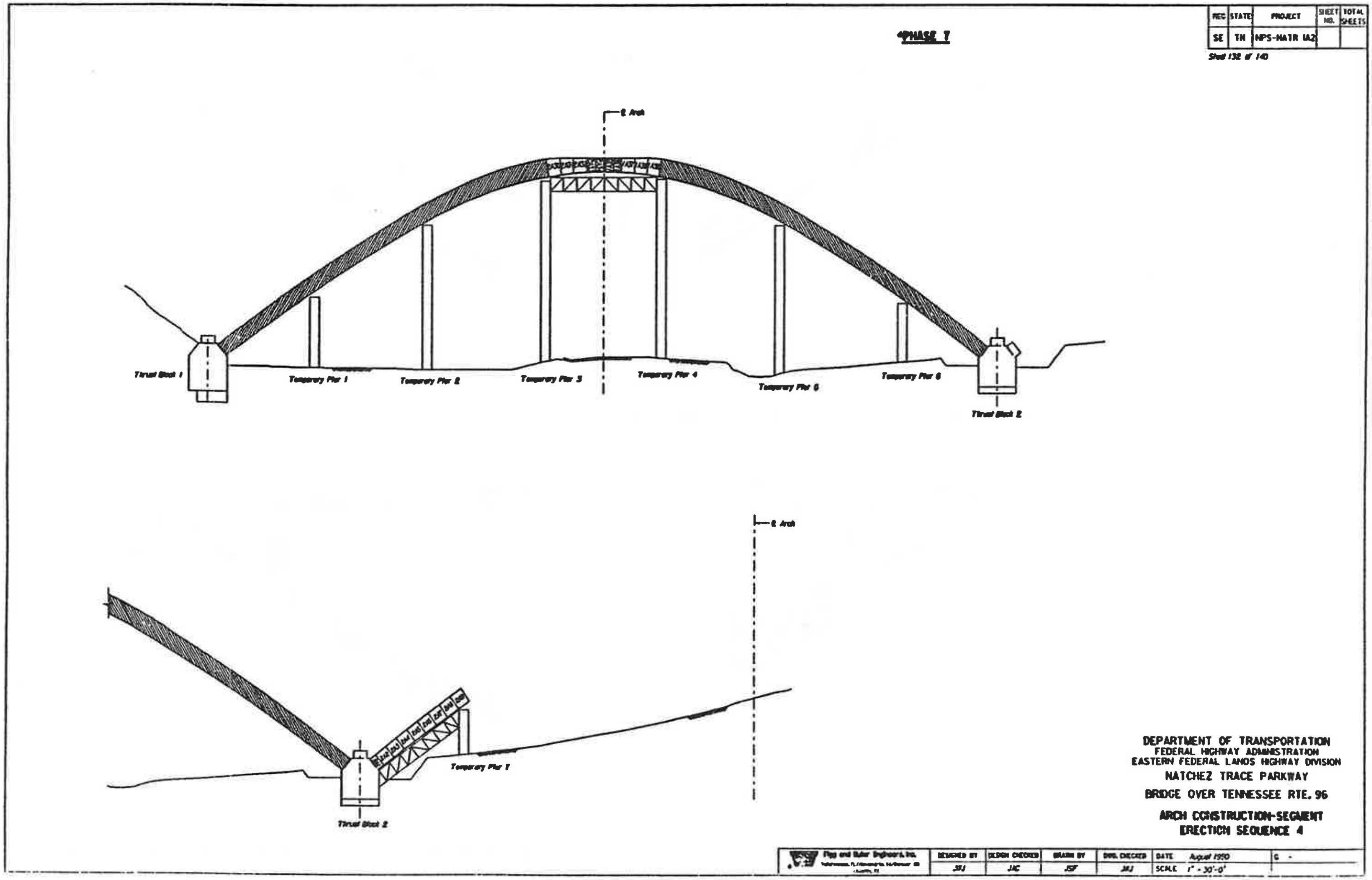

FIGURE 15 Arch construction - precast alternate - phases 7 and 8

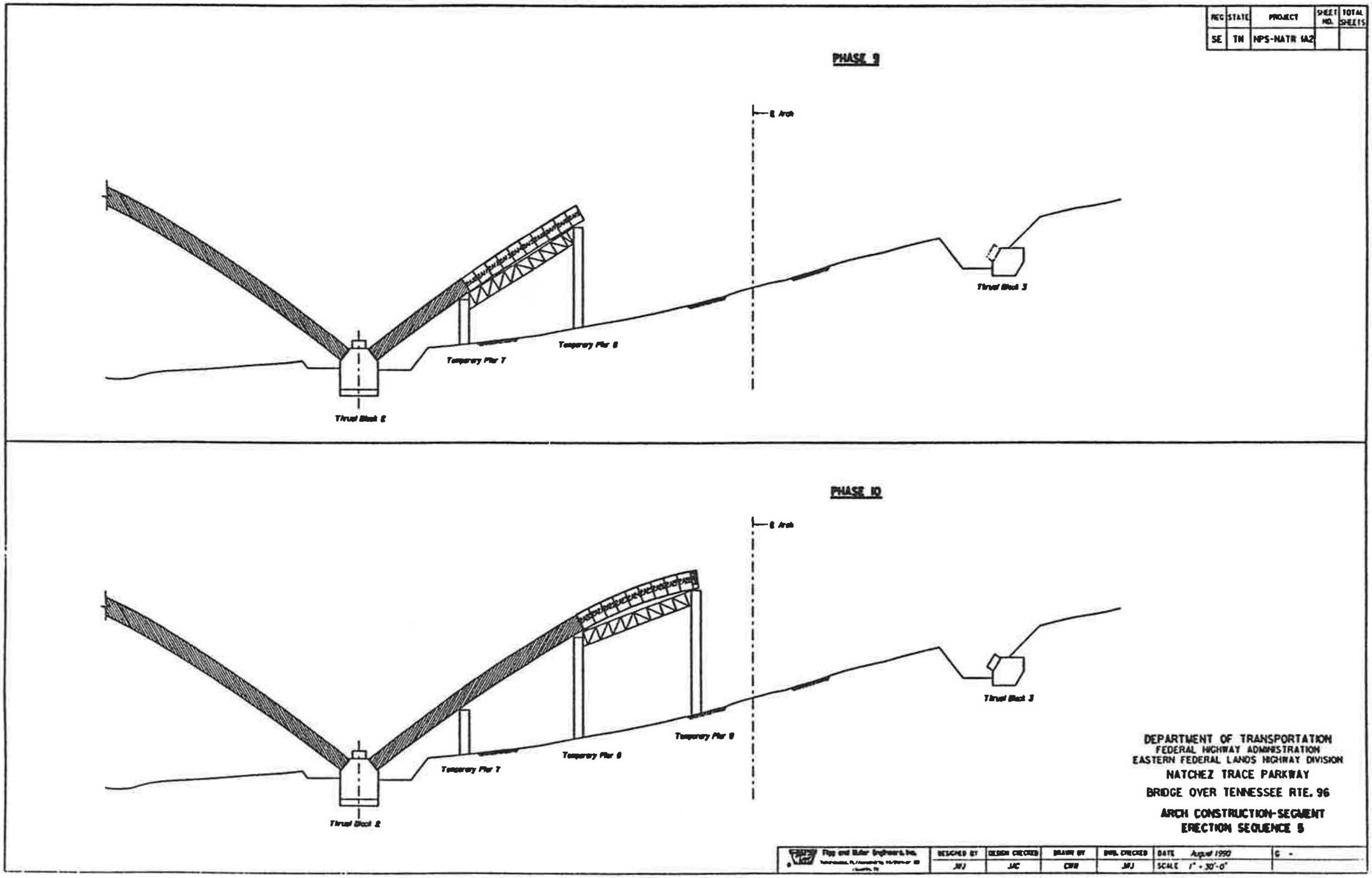

FIGURE 16 Arch construction - precast alternate - phases 9 and 10

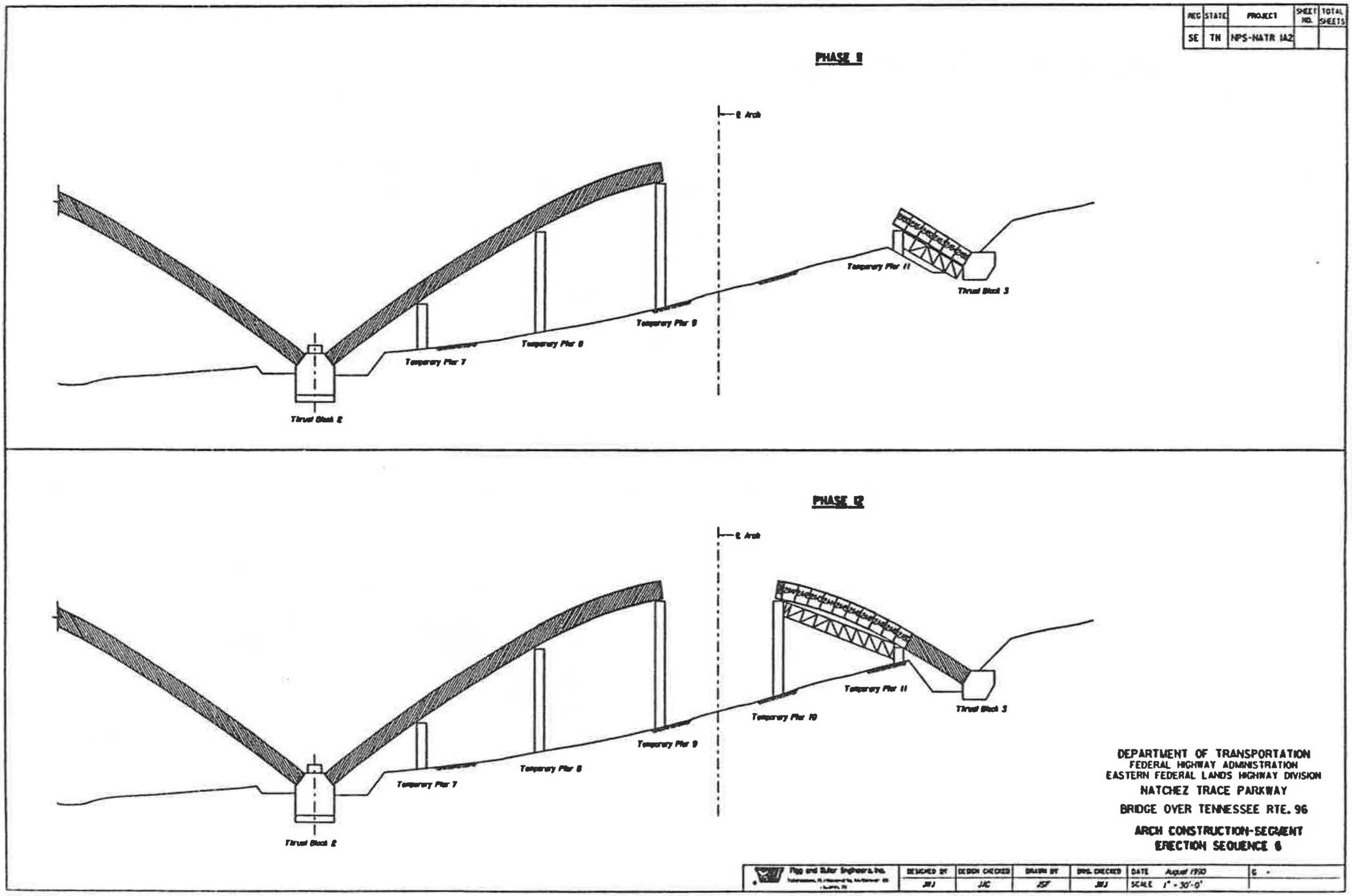

FIGURE 17 Arch construction - precast alternate - phases 11 and 12

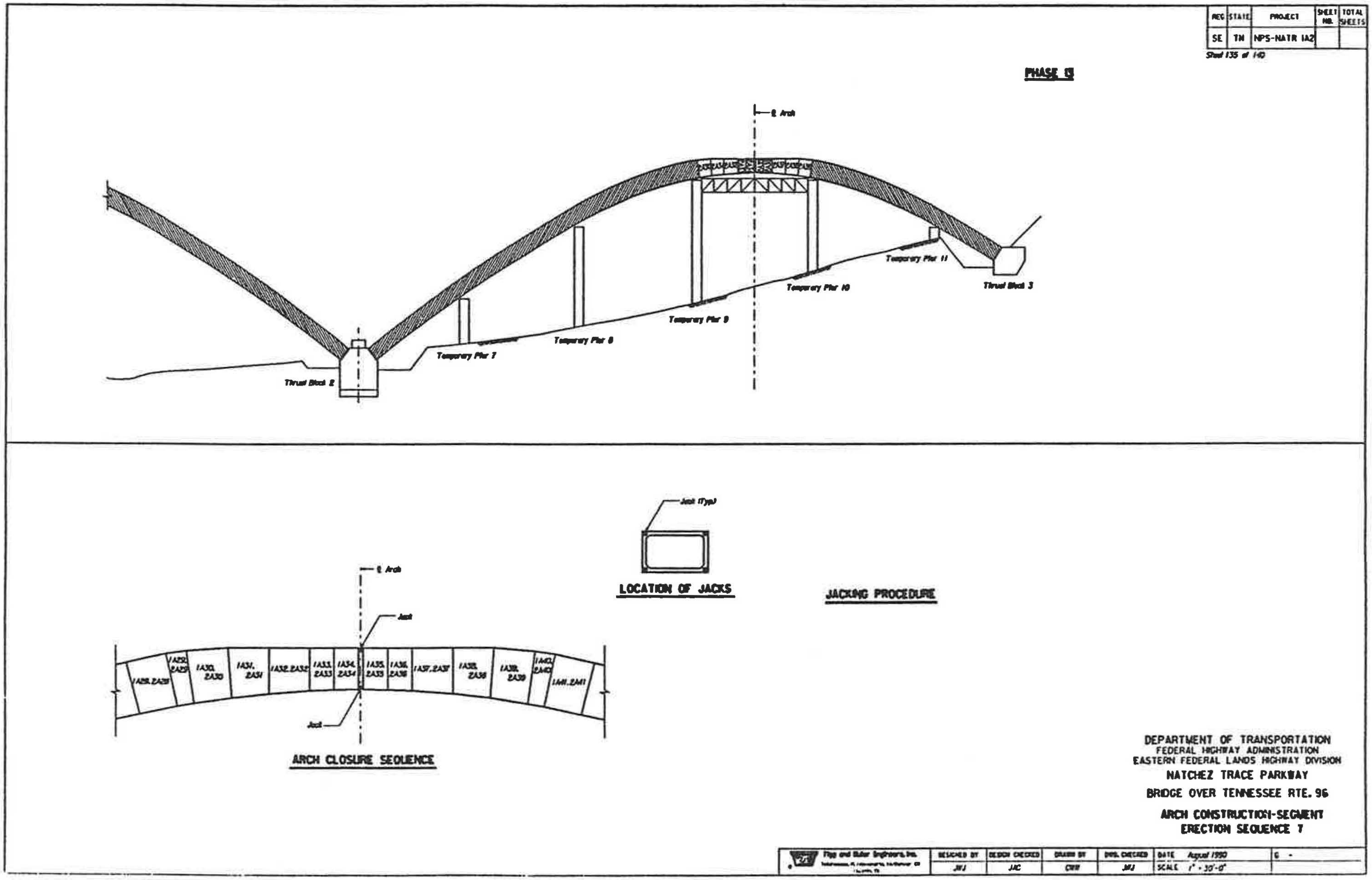

FIGURE 18 Arch construction - precast alternate - phase 13

Construction of arch 2 proceeds in similar fashion except that having a span of 462 feet, it contains only six intermediate spans.

Superstructure

A total of 196 precast segments are used to build the bridge superstructure. The typical segment length is 8 feet 6 inches. Maximum segment weight is 55 tons and minimum segment weight is 36 tons.

The superstructure of the bridge is designed to be constructed primarily by the balanced cantilever method of construction. Special modifications to this method are made for assembling the precast box girder segments adjacent to the abutments.

Erection begins after all precast piers and arch segments have been assembled, as shown in Figures 19 through 21. Access by ground-mounted crane is permissible for the entire length of the project except for the first 204-foot span. A steep slope rising approximately 150 feet over the span's length must not be marred by any of the construction activity. This requires a travelling beam-and-winch system for the construction of the first cantilever. The system must travel from a staging area at the base of pier 1, where segments are delivered, to the ends of the cantilever where the segment is being erected. This beam and winch has its rigging outside the width of the box girder to permit free passage of the segments.

The cantilever over arch 1 is assembled next. This cantilever is actually made up of two smaller cantilevers of six segments each. These smaller cantilevers are built about the bearing location of the bridge deck on the arch (45 feet off of centerline of arch). When each of the cantilevers are complete to a length of six segments, a 6-inch closure joint is poured over the centerline of the arch. Construction then continues on the now larger cantilever until reaching its full length in the 246-foot spans.

The construction procedure continues with balanced cantilever assembly over pier 2 with segments placed by a ground-based crane, or with the beam-and-winch system previously described, over arch 2 as previously described above, and over pier 3.

The last areas of segment placement are the approximately 70 feet of the first and last spans. As previously mentioned, this area near abutment 1 is not available for any construction activity. To overcome this difficulty, incremental launching techniques were investigated. Several options were investigated with regard to maintaining the stability of the segments being launched. It was decided to combine balanced cantilever construction with the concepts of incremental launching using the similar segments from the last span to build a complete cantilever.

Twin stub walls, 140 feet long, are built behind the back of abutment 1 bearing seats. These stub walls serve as the tracks for incrementally launching the first span. A balanced cantilever erection sequence is begun for a length of 140 feet on the stub walls, as shown in Figures 22 and 23. Segments from span 1 are used in their final location while the similar segments from the last span are used on the opposite side of the cantilever. When the balanced cantilever construction is complete, the girder is launched forward until the abutment segment comes to rest over the final bearings. The closure joint of span 1 is poured and the continuity post-tensioning is stressed, thus completing span 1. This is followed by the slackening of the cantilever tenndons and the removal of the segments of the last span. These segments are transported to the opposite end of the project where they will be assembled on falsework. After all tendons are stressed, the abutment backwalls are poured and the erection is complete.

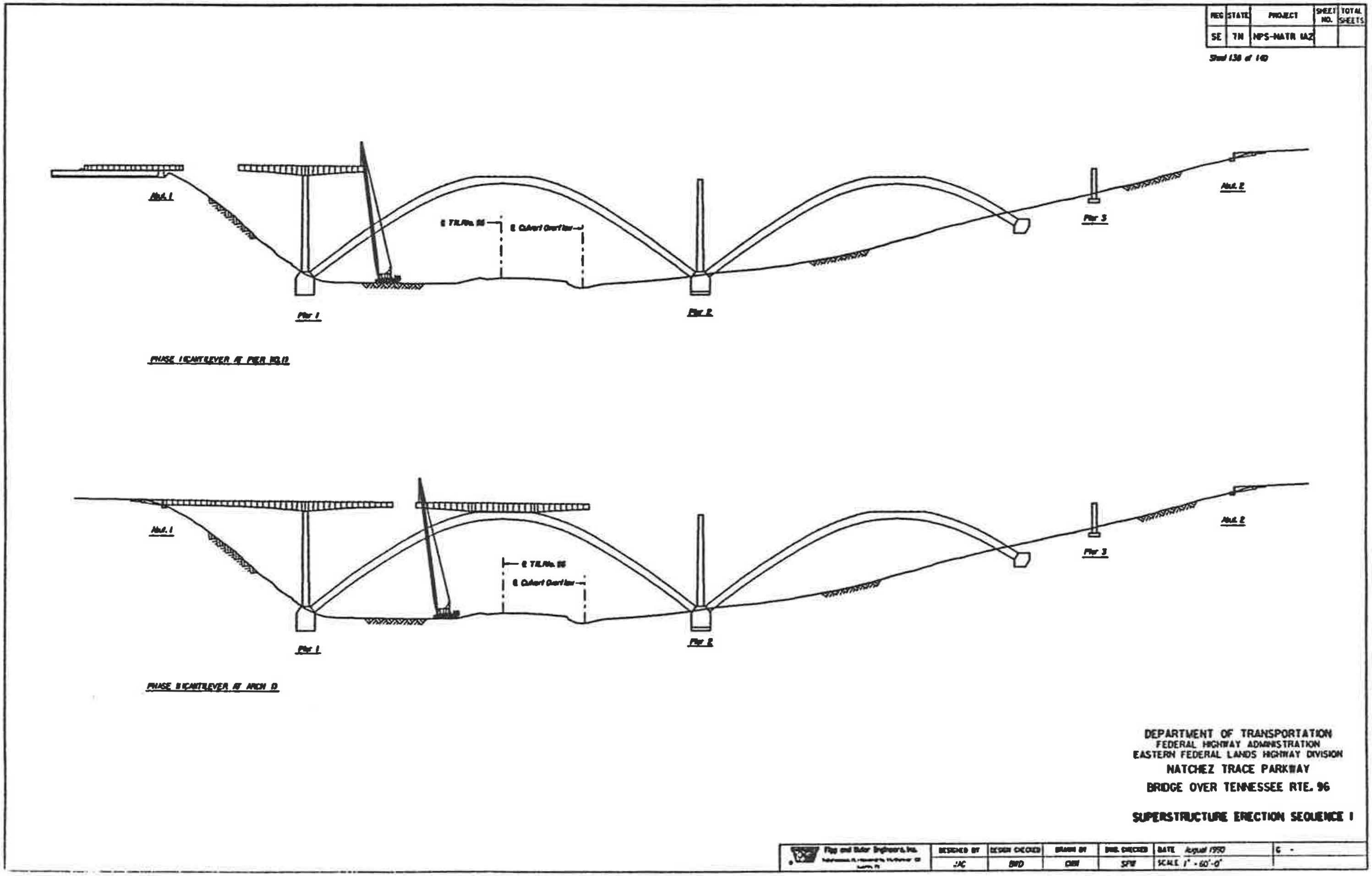

FIGURE 19 Superstructure construction - precast alternate - phases 1 and 2

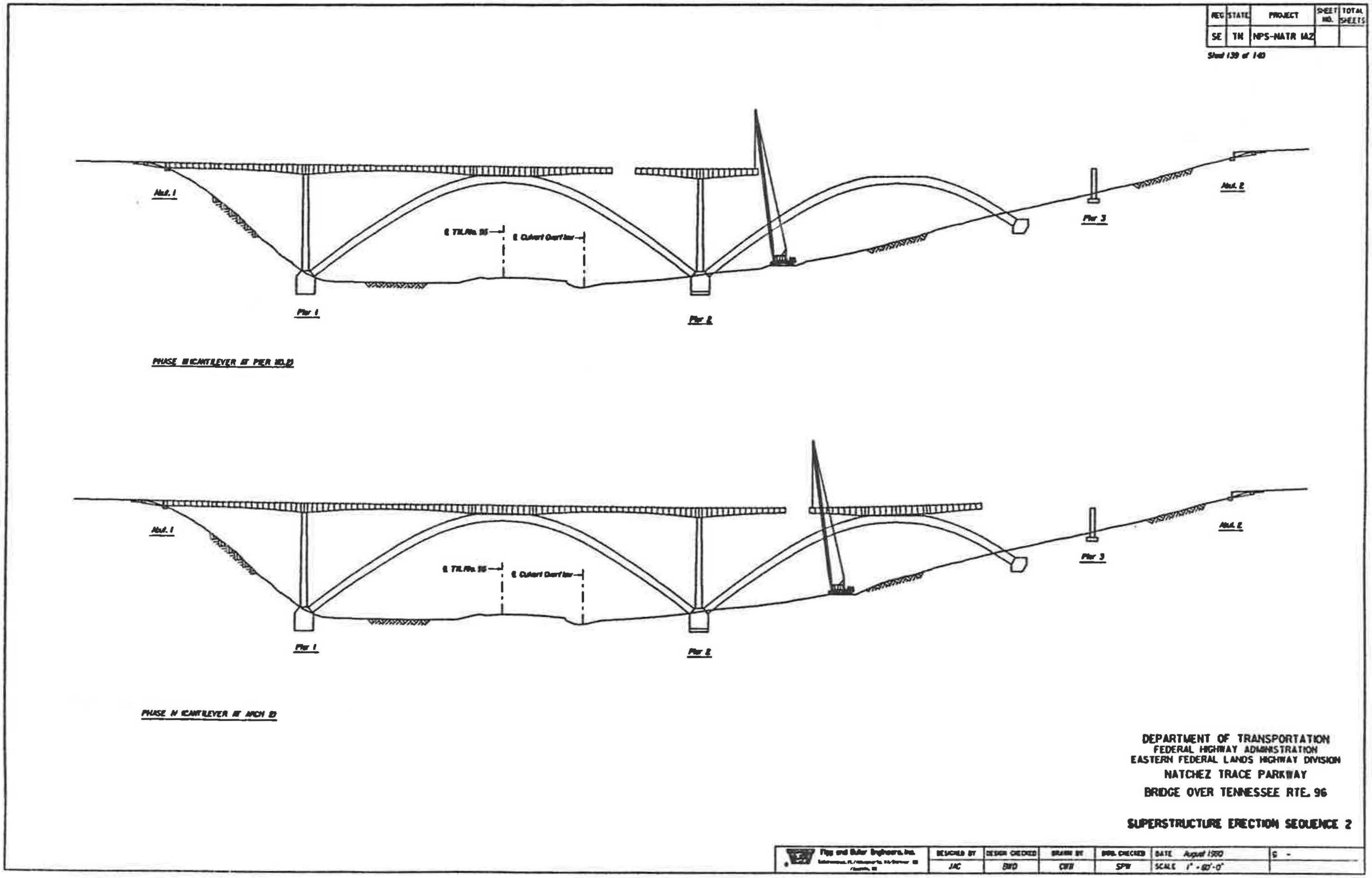

FIGURE 20 Superstructure construction - precast alternate - phases 3 and 4

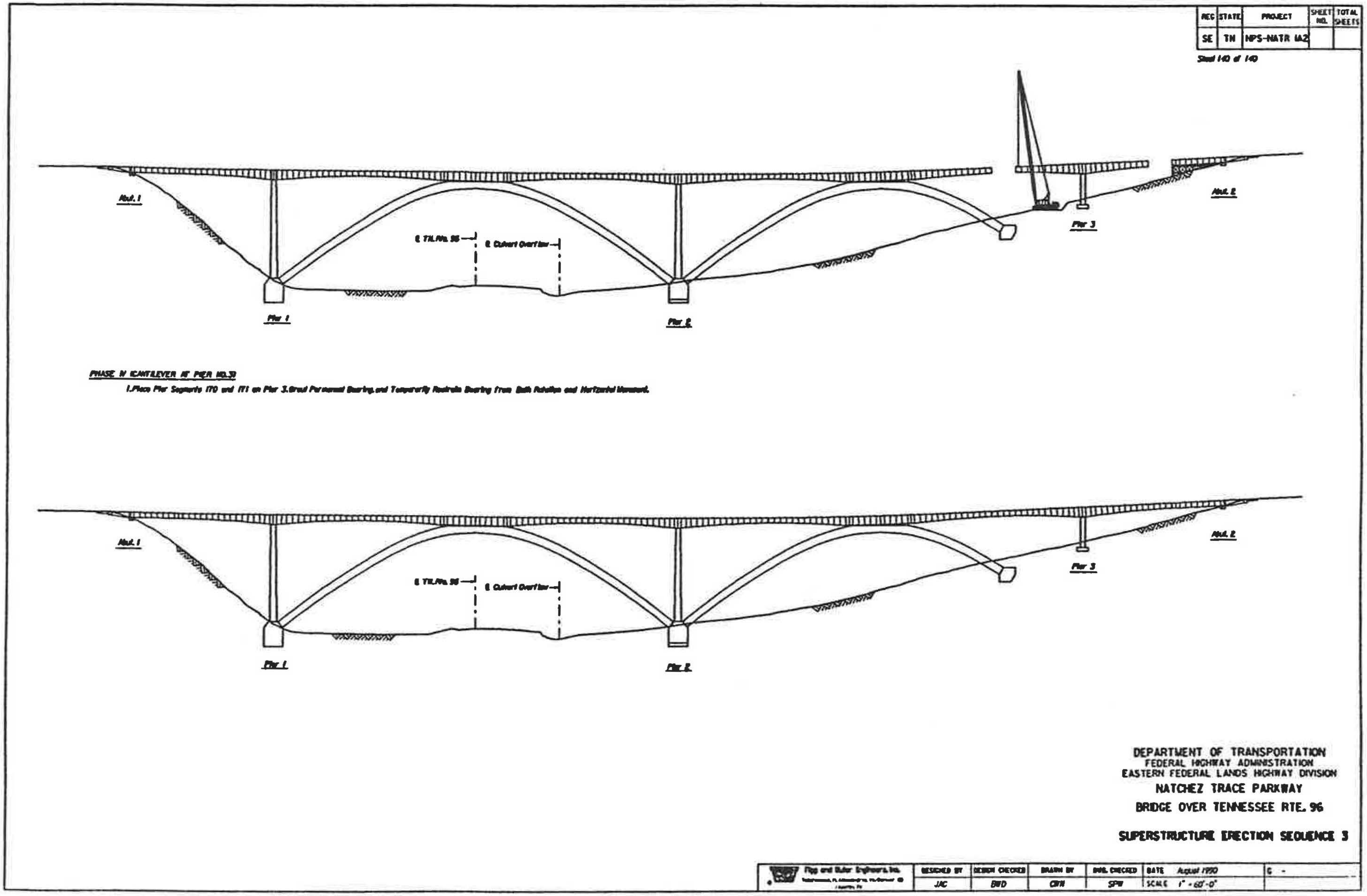

FIGURE 21 Superstructure construction - precast alternate - phases 5 and 6

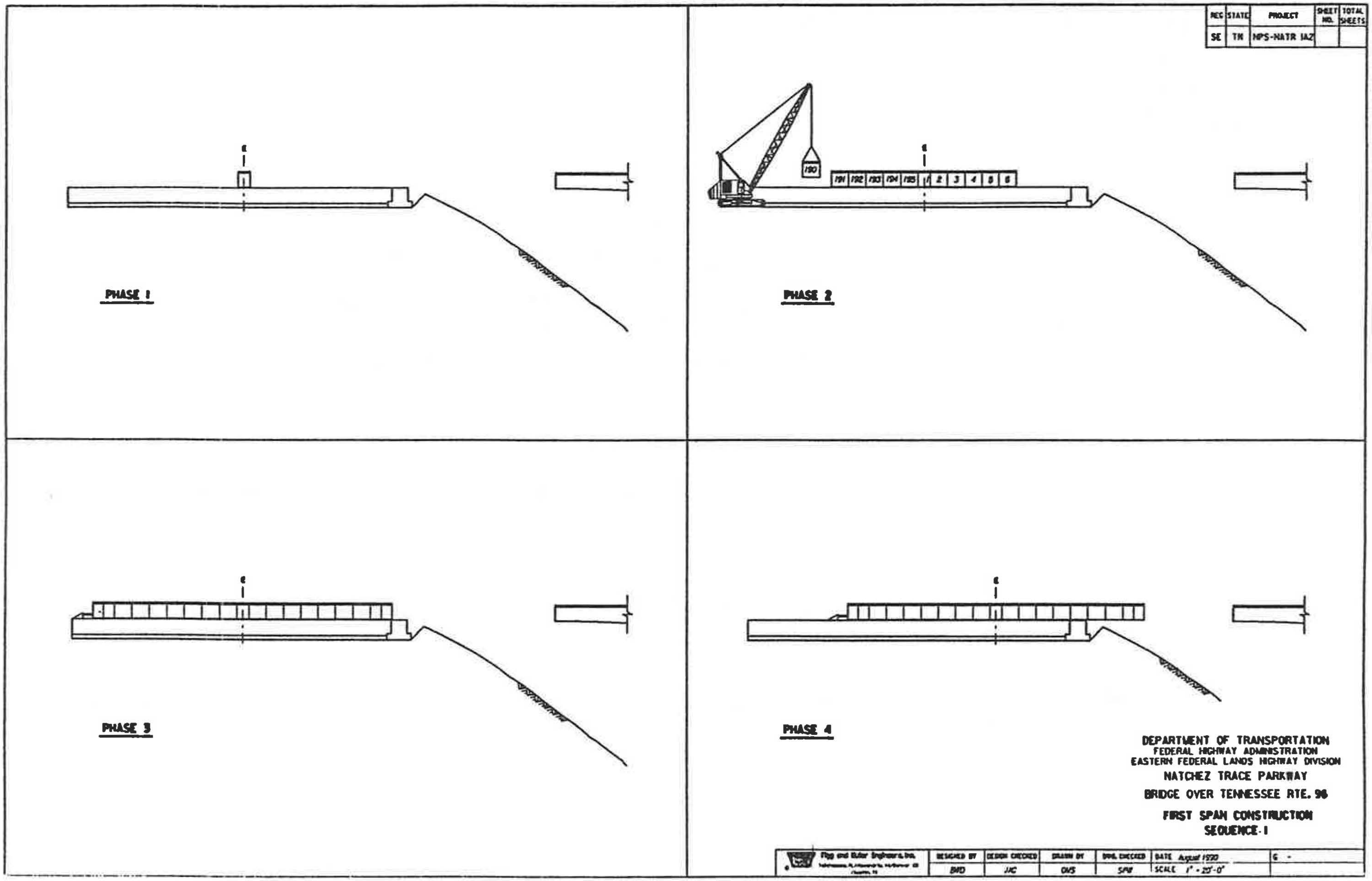

FIGURE 22 First span construction - precast alternate - phases 1 through 4

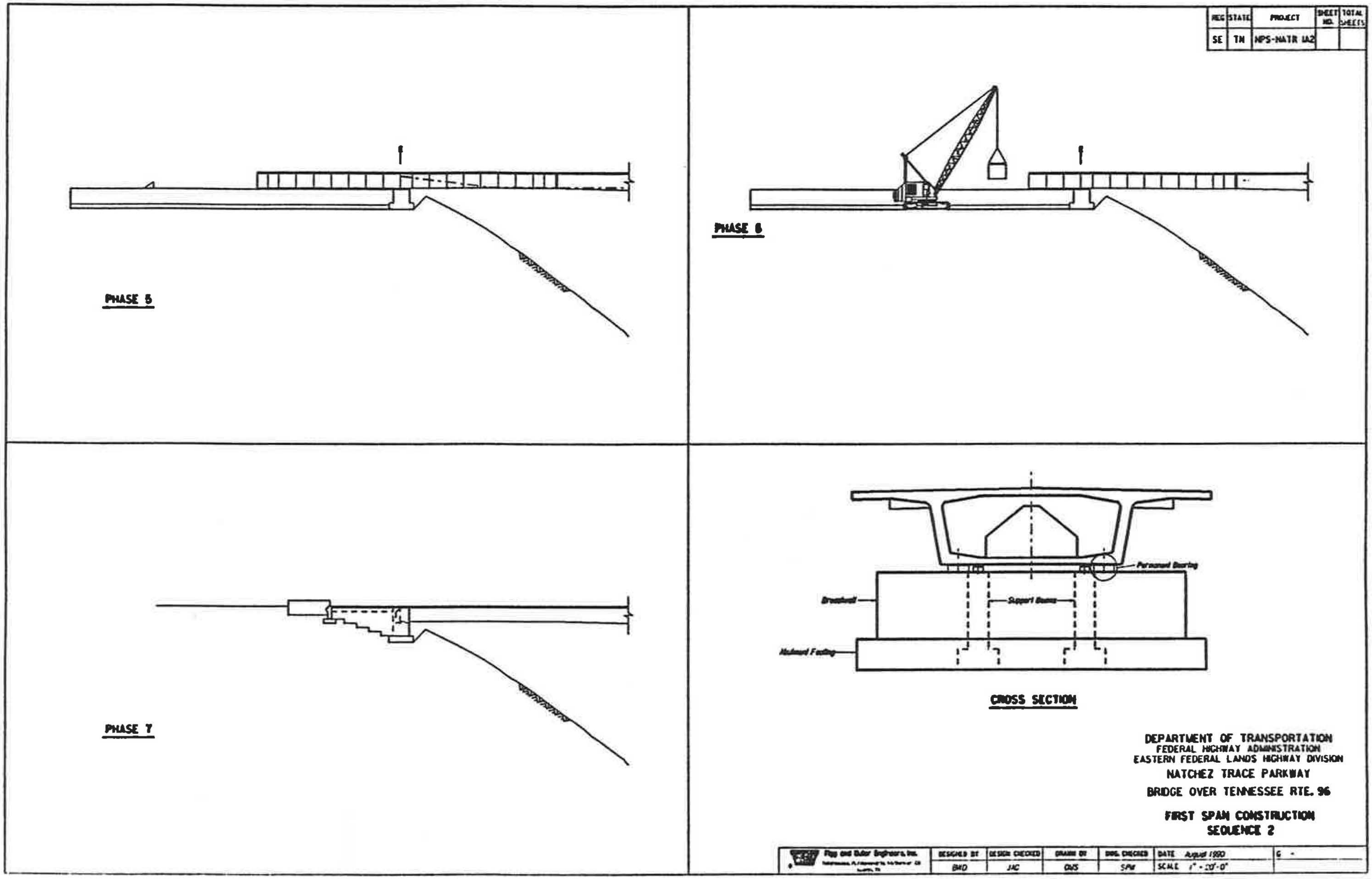

FIGURE 23 First span construction - precast alternate - phases 5, 6, and 7