PHX Sky Train Stage 2 at Phoenix Sky Harbor International Airport

by Andrew Mish, Modjeski and Masters Inc.

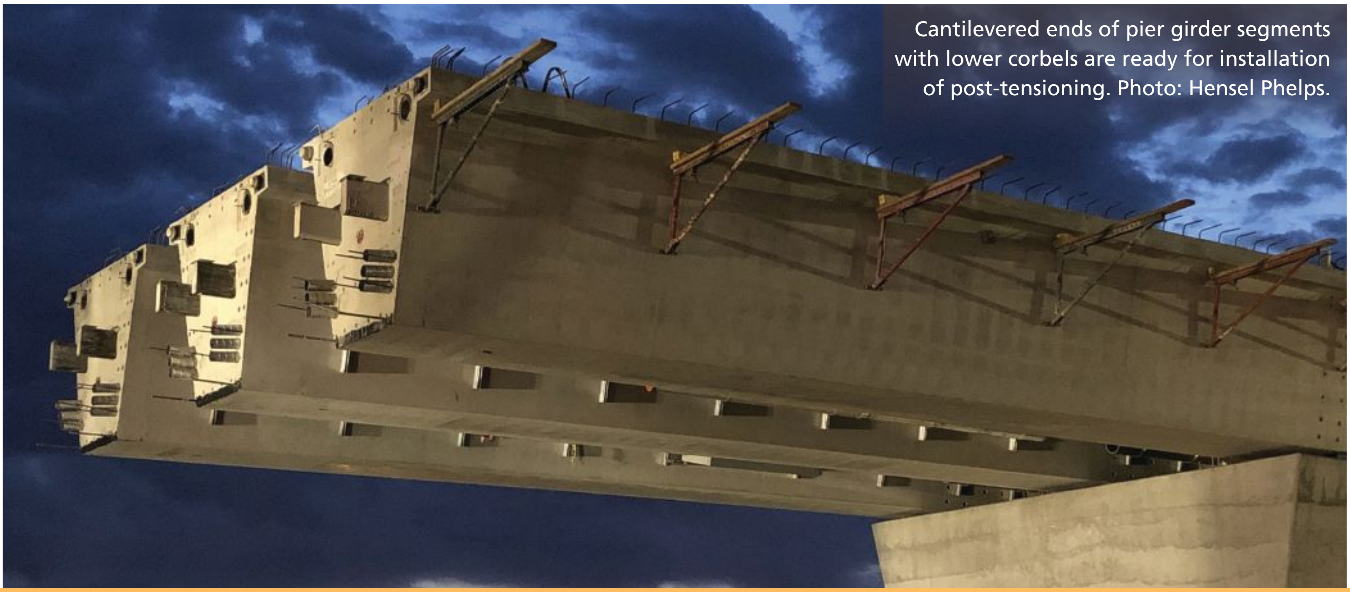
The Phoenix Sky Harbor International Airport (PHX) is poised to see a significant increase in the number of travelers using the facility in the coming years. According to the City of Phoenix Aviation Department, 2019 was a record year for PHX, with just shy of 46.3 million passengers traveling through the airport. This was a 5% increase over the nearly 44 million passengers using the PHX facility just two years prior, in 2017.

To handle the increasing volume of PHX travelers, the City of Phoenix has undertaken a nearly $2 billion capital investment program to expand and improve airport services. A major part of this program is the Stage 2 project to build a 2.2-mile extension of the Phoenix Sky Train from Terminal 3 to the Rental Car Center. This extension will provide a direct link for passengers between the airport and the Rental Car Center. The trains will depart every 3 to 5 minutes with a travel time of 8 minutes to and from the terminals, providing a significant improvement to the current shuttle bus system, which can require up to 30 minutes of wait and travel time.

Construction is ongoing; however, precast concrete element delivery is complete, with terminal construction and train testing to run through 2021. Upon the project's completion, scheduled in 2022, the extension will allow the automated train to run from the Rental Car Center east through the airport, with stops at all existing passenger terminals and a new passenger drop-off/pickup station, before terminating at the 44th Street Station, which connects to the Valley Metro Rail serving Phoenix and other local communities.

Stage 2 Extension Bridges

Stage 2 of the Phoenix Sky Train provides two guideways for automated trains. The project lengthens the existing tracks by approximately 2.2 miles with nearly 7000 ft on guideway bridges. The guideway bridges support the



Cantilevered ends of pier girder segments with lower corbels are ready for installation of post-tensioning. Photo: Hensel Phelps.

profile

PHX SKY TRAIN AT PHOENIX SKY HARBOR INTERNATIONAL AIRPORT, STAGE 2 / PHOENIX, ARIZONA

BRIDGE DESIGN ENGINEER: Gannett Fleming, Phoenix, Ariz.

PRECAST CONCRETE ENGINEER: Modjeski and Masters Inc., Littleton, Colo.

PRIME CONTRACTOR: Hensel Phelps, Phoenix, Ariz.

TEMPORARY WORKS SUBCONTRACTOR: Pulice Construction, Phoenix, Ariz.

PRECASTER: EnCon Arizona LLC, Phoenix, Ariz., dba Tpac—a PCI-certified producer

PRECAST CONCRETE FORM SUPPLIER: Helser Industries, Tualatin, Ore.

automated people mover system, which consists of Bombardier Innovia APM 200 vehicles. Live loads used for design were provided by the vehicle manufacturer and based on the vehicle configurations that can be used with the system. The extension also includes two depressed sections to carry trains underneath two future aircraft taxiway bridges.

The elevated guideway bridges include 80 spans of precast concrete U-girders, which vary in length from 55 to 198 ft. The substructure consists of 5- to 6-ft-deep concrete pier caps on single- or double-column piers founded on drilled shafts. The column diameters range from 5 to 8 ft. All substructure concrete was cast-in-place.

The two taxiway bridges are single-span structures, which vary in length from 33 to 35 ft and are composed of precast concrete voided rectangular box girders. The project also includes a facilities access road bridge constructed using precast concrete voided slab girders with a single span of 42 ft.

In total, the bridges constructed in Stage 2 used 446 individual precast concrete girders, including two hundred ninety-six 60-in.-deep precast concrete U-girders, twenty-four 78-in.-deep precast concrete U-girders, 118 precast concrete voided rectangular box girders, and eight precast concrete voided slabs. The 78-in.-deep U-girders were used in a continuous, post-tensioned (PT) bridge unit that was constructed to span over an existing and active airport terminal building and a future taxiway. Although the bridge alignment was curved at some locations, it was possible to use straight girder segments to construct the PT bridge unit. The terminal building, Terminal 2, was in use during construction, but it saw its last flight in February 2020 and is scheduled for demolition over the next year. This unit required special staged construction analysis and significant temporary works (for details, see the Concrete Bridge Technology article on page 34).

Project Delivery

To speed project delivery from design through construction, the owner decided to use a construction manager at risk (CMAR) method. With this method, the owner retains the design team to start the design process. Once significant progress has been made on the design, typically 30% to 60%, the owner initiates a second contract to hire a construction manager. The designer and construction manager collaborate as the design progresses into the final stages. The construction manager provides input on constructability and can offer insights to the designer that may add value to the project. The CMAR arrangement also allows for earlier starts to construction activities. Once the design is significantly complete, the construction manager provides a guaranteed maximum price to the owner to construct the project.

The precaster selected for the project engaged a design firm that had expertise with precast, PT concrete design and construction to provide precast concrete engineering services.

Project Team Collaboration

One of the key components contributing to the success of the project was the collaboration of the project team. The precaster selected for the project engaged a design firm that had expertise with precast, PT concrete design and construction to provide precast concrete engineering services. The designer, contractor, precaster, and precast concrete engineer met regularly to develop the concepts and procedures that would be incorporated into the final design and construction process.

All parties invested in the success of the project and shared ideas openly throughout the entire design process. When 60-in.-deep pretensioned concrete U-girders were selected as the typical girder system for the skyway bridges, the precaster shared the capabilities of its U-girder casting beds to ensure that the designs considered the girder section and tensioning capacity of the casting facility. All girders used straight strand patterns of 0.6-in.-diameter strands, with up to 51 strands per girder. The design used a combination of debonding and top strands to control top tensile stresses at transfer of the pretensioning force. The 60-in.-deep U-girders varied in length from 55 to 103 ft and were used on the pretensioned simple-span portions of the elevated guideway bridges. For the continuous PT bridge unit, the final design used 78-in.-deep U-girders to achieve the longer spans needed to span across the future taxiway and over the existing Terminal 2 building. Arriving at this cross section was a collaborative process among the precaster, precast concrete engineer, contractor, and designer. The precaster needed to modify its existing forms to cast the 78-in.-deep sections. Girder weights were an important consideration for handling at the precast plant, shipment to the jobsite, and crane capacity for erection. All parties worked together to achieve the final design solution.

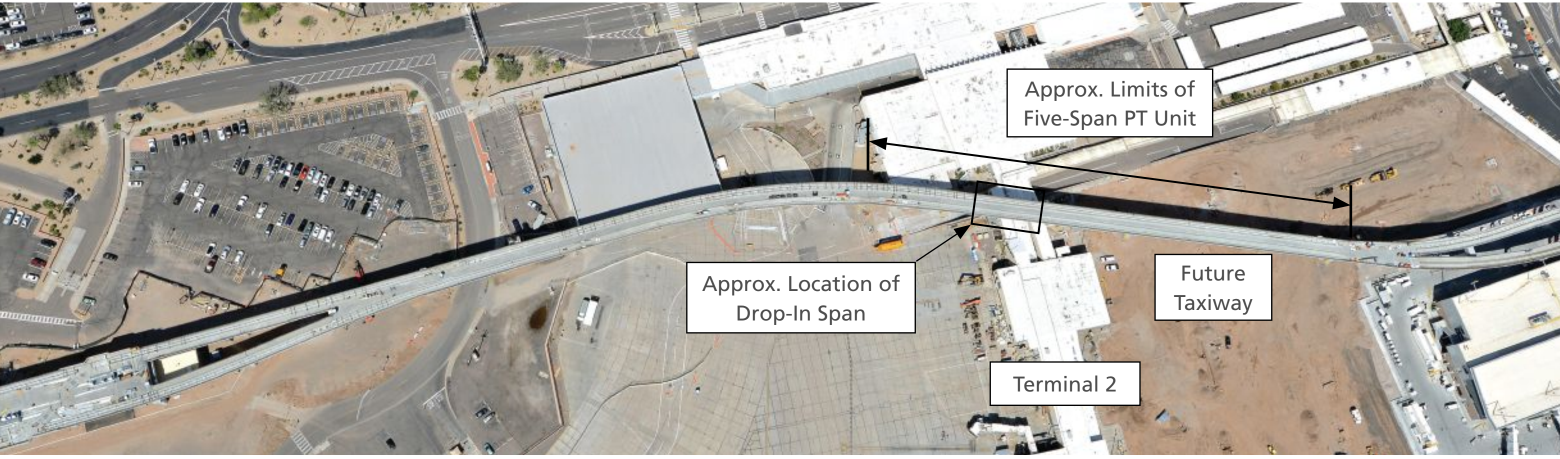
CITY OF PHOENIX AVIATION DEPARTMENT, OWNER

POST-TENSIONING SUPPLIER: DYWIDAG Systems International, Long Beach, Calif.

PROJECT DESCRIPTION: 2.2-mile-long extension of the automated train system, including 6988 ft on guideway bridges, to connect Terminal 3 of the airport to the Rental Car Center. The project included a 676-ft-long five-span, continuous post-tensioned superstructure unit with drop-in girder segments that crosses a future taxiway and a terminal building.

STRUCTURAL COMPONENTS: Two hundred ninety-six 60-in.-deep precast, pretensioned concrete U-girders, twenty-four 78-in.-deep precast, post-tensioned concrete U-girders, 118 precast concrete voided rectangular box girders, and eight precast concrete voided slabs; cast-in-place concrete composite deck slab; cast-in-place concrete pier caps on single- or double-column piers founded on drilled shafts

PHX SKY TRAIN TOTAL PROJECT BUDGET: $745 million



Aerial view of the completed PHX Sky Train guideway structure, including the five-span continuous PT unit, drop-in span, and other major features. Photo: Tpac.

Site Conditions and Construction Challenges

Constructing more than 2 miles of guideway track through an existing airport presented numerous challenges. Buried utilities had to be avoided, relocated, or carried by the new structures. Pier locations were constrained by underground utilities and clearance to existing building structures, and an access road running under the terminal walkway further restricted site access and limited crane placement, falsework locations, and girder delivery. Aircraft taxiways needed to be accommodated, and existing facility buildings had to remain operational. Most importantly, while passengers could see that construction was occurring, the owner did not want their traveling experience to be significantly affected by the project.

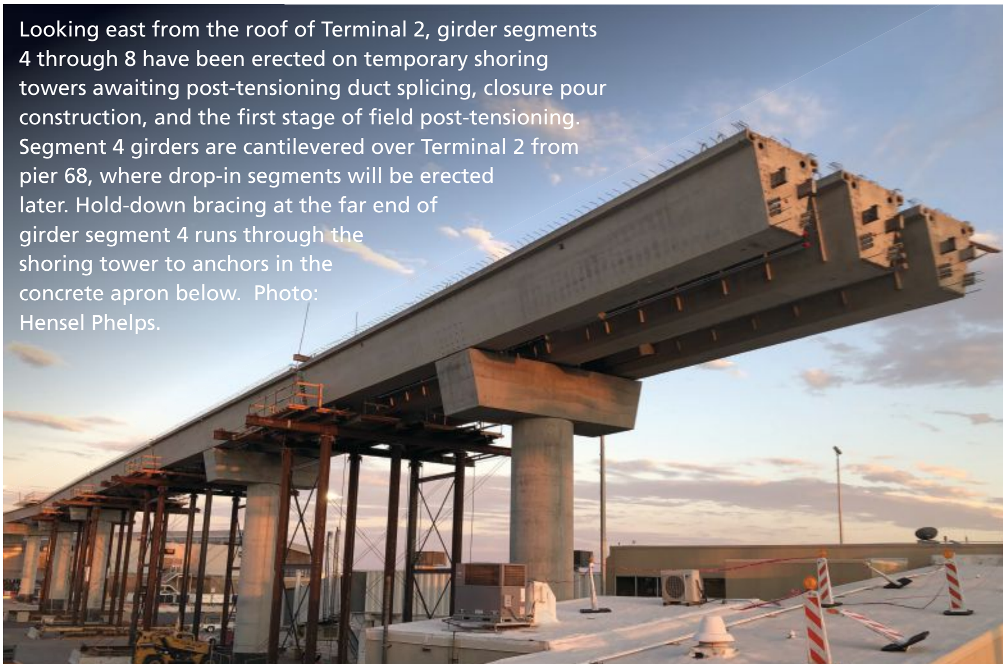
One of the more challenging design issues was the design and construction of a bridge unit over Terminal 2 and a future taxiway. Because the terminal building needed to remain in use, girder erection activities over the terminal building were restricted to the hours between 10:00 p.m. and 4:00 a.m.—from deplaning of the final flight in the terminal to morning access for the workers preparing for the first flights on the following day. Because of site constraints, falsework towers could not be located to support the girders spanning directly over the building. Special staged construction methods using embedded corbels were designed for this bridge unit to allow the girder segments over the terminal to be hung from the adjacent girder segments that cantilevered beyond the piers during this stage of construction. This meant that there was a compressed time window to complete the most complicated girder erection for the project.

Beyond the challenge of the existing conditions, the design of this bridge unit also had to span a future aircraft taxiway. The design for the taxiway required a 162-ft-wide, 40-ft-tall obstacle-free area to accommodate the aircraft clearance envelope. A span of 198 ft was required over the future taxiway, and a span of 163 ft was required to accommodate the crossing of the existing terminal building. These requirements exceeded the simple-span capabilities of the 60-in.-deep U-girders used for most of the other guideway bridges. Given the combined site constraints and longer spans required for the taxiway and terminal building in this bridge unit, the project team determined that a staged, PT structure was the ideal solution. To meet this challenge, the engineer of record led the design effort for a five-span precast, PT concrete superstructure unit at this location; this design used precast concrete U-girders to maintain a cohesive aesthetic with the rest of the elevated guideway. After an iterative design process with input from all team members, 78-in.-deep U-girders were chosen to accomplish the design objectives for this unit.

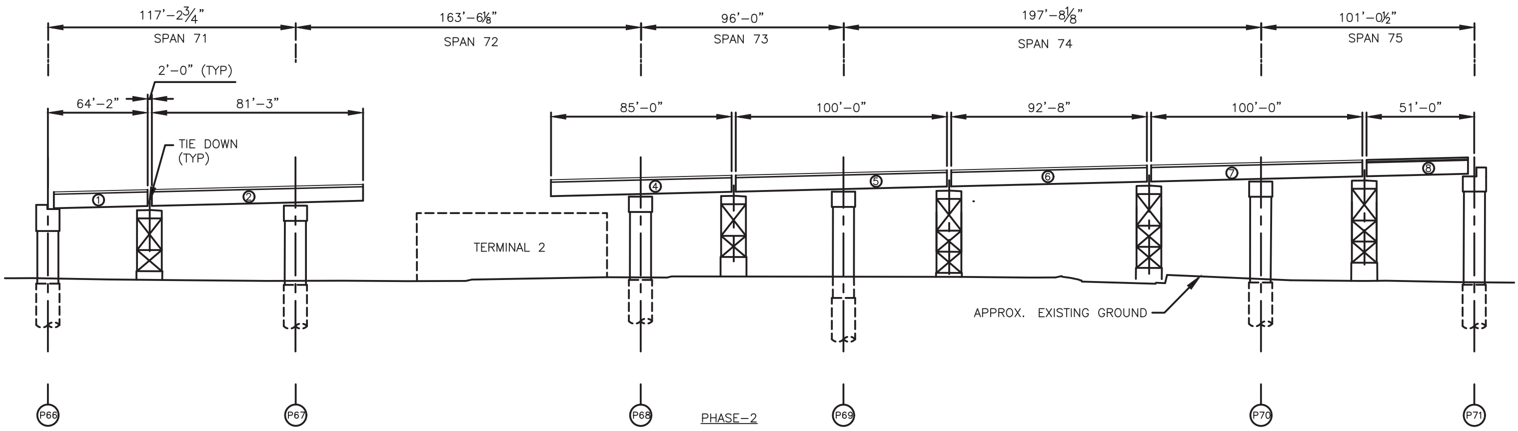
Precast Concrete Engineering and Staged Construction

For the challenging bridge unit at Terminal 2, the precaster, precast concrete engineer, and engineer of record for the project worked together to deliver a girder section that could be cast with only minor modifications to the precaster's existing U-girder forms. The final design specified 78-in.-deep post-tensioned U-girders; these were deeper than the precaster's existing forms and had thicker webs to accommodate the post-tensioning ducts while maintaining adequate clear cover to the web reinforcement. The formwork was designed to retrofit the precaster's existing U-girder forms, which helped minimize fabrication costs and reduce lead time for the formwork fabrication, delivery, and assembly.

The five-span PT unit is composed of three girder lines with eight precast



Looking east from the roof of Terminal 2, girder segments 4 through 8 have been erected on temporary shoring towers awaiting post-tensioning duct splicing, closure pour construction, and the first stage of field post-tensioning. Segment 4 girders are cantilevered over Terminal 2 from pier 68, where drop-in segments will be erected later. Hold-down bracing at the far end of girder segment 4 runs through the shoring tower to anchors in the concrete apron below. Photo: Hensel Phelps.



Original erection schematic from design plans for the five-span post-tensioned unit, with all girder segments erected except the drop-in segment, which was 87 ft 3 in. long. During construction, the shoring tower shown in span 71 was moved 20 ft closer to pier 67 and girder segment lengths were adjusted accordingly. This move caused erection stability concerns when placing segment 2 girders in their cantilevered position. Sufficient stability was provided with girder ballast and hold-down bracing at the temporary support. These stability measures were also necessary for segment 4 girders. Figure: Gannett Fleming.

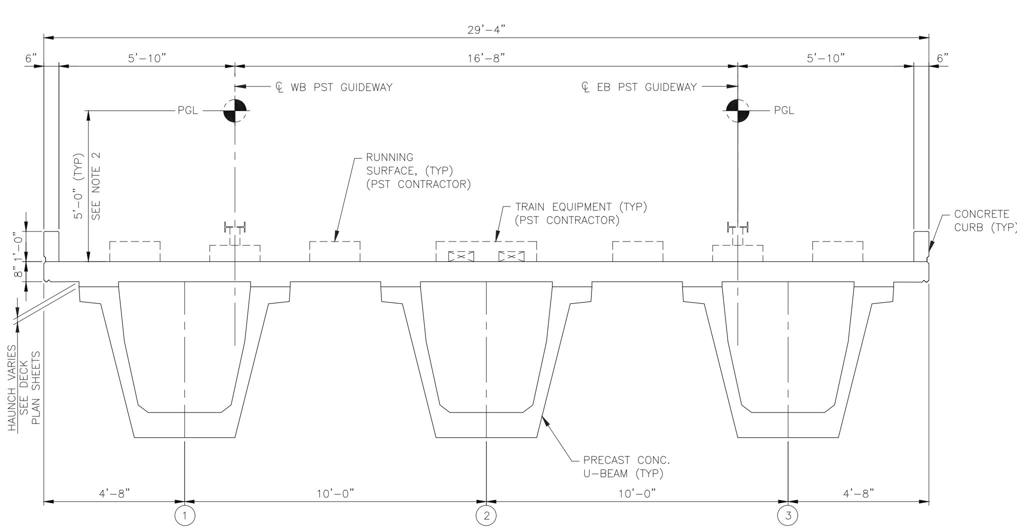
concrete girder segments in each girder line. The girder segments vary in length from 53 to 100 ft and weigh up to 210 kip. Because of the restrictive site conditions, the span over the terminal building was designed to be erected with drop-in girder segments supported using embedded hollow structural section (HSS) steel corbels. This required staged erection and post-tensioning. Girder segments 1 and 2 and girder segments 4 through 8 were erected on each side of the terminal building. Girder segments 2 and 4 spanned from falsework towers to piers with cantilevers beyond the piers. Girder segment 2 required temporary ballast weight and hold-down rods to provide a sufficient factor of safety against overturning of the segment prior to the casting of splices with girder segment 1. Following the erection of these girder segments, reinforcement was placed and ducts were spliced in the closure. Concrete was then placed between the erected segments. Pier diaphragms were also cast at this stage, with reinforcing bars placed through sleeves in the girder webs and threaded reinforcing bar couplers in the bottom slab to make an integral connection with the girders.

Next, two PT tendons, each consisting of twelve 0.6-in.-diameter strands, were tensioned. Because girder segments 2 and 4 cantilevered beyond the supporting piers, this post-tensioning—in combination with two top-flange PT tendons consisting of four 0.6-in.-diameter strands installed at the precast plant—provided the negative moment capacity to support the drop-in girder segments. These tendons were incorporated into the final design. After the drop-in girder segments were erected and the splices completed, six continuity PT tendons were tensioned and grouted in each girder line for the full-length of the unit. A composite deck slab was then cast on the girders to complete the superstructure.

Instead of using external strongbacks to support the drop-in girders over the terminal building, an embedded corbel system was designed and cast into the precast concrete girders. The corbels were composed of concrete-filled HSS tubes with welded bearing plates. Only two erection bolts per corbel were required to make the connection during erection. Given the brief erection window, this was very important because it eliminated the time that would have been needed to connect external strongback hardware to the girders. For more details on the corbel connection, see the Concrete Bridge Technology article on page xx.

This project is a testament to the flexibility and versatility of precast concrete construction. When design and construction teams collaborate, innovative solutions can be achieved safely and economically. PT concrete structures expand the bridge designer's toolbox and offer solutions to unique and complex bridge construction challenges.

Andrew Mish is project manager and office manager at Modjeski and Masters Inc. in Littleton, Colo.



Typical section for 60-in.-deep U-girder spans. The typical section for the spliced 78-in.-deep U-girder spans is similar. Figure: Gannett Fleming.