Making Connections: Design of Airfield Bridges at Phoenix Sky Harbor International Airport

Andrew Ward, P.Eng.
Senior Bridge Engineer
Gannett Fleming
Toronto, Ontario
award@gfnet.com

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Abstract

Bridges supporting taxiways carrying commercial aircraft remain relatively rare. Due to increased air travel demand, combined with increased development limiting airport expansion, the necessity of these bridges is increasing. Phoenix Sky Harbor International Airport, which services over 400,000 takeoffs and landings each year, is in the midst of a vital project to expand access between the north and south airfields through the construction of Crossfield Taxiway “U”.

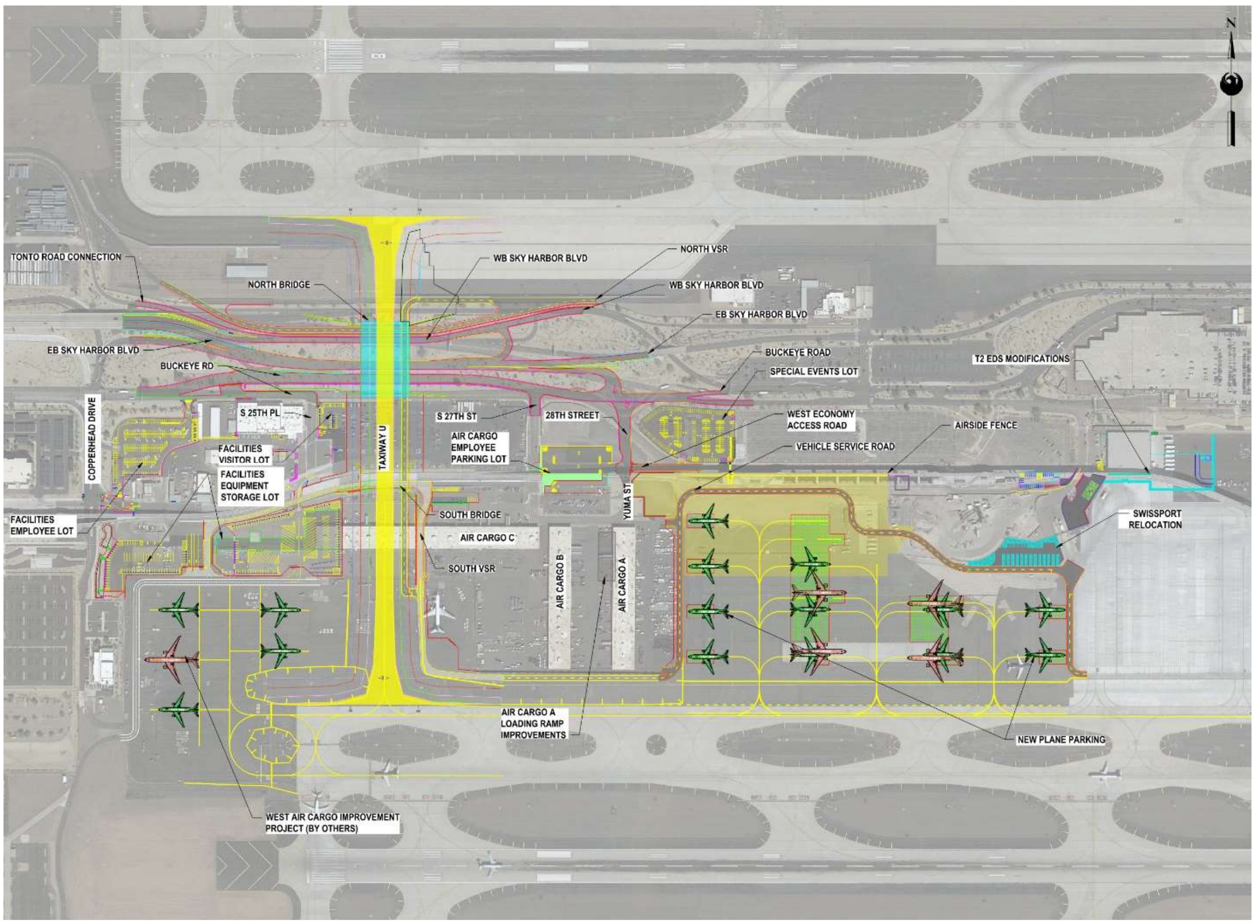
This Construction Manager At-Risk (CMAR) project will include two new bridges to carry the taxiway, as well as 14 retaining walls. One of the bridges will cross over the airport’s main access roadways, which will be lowered by approximately 18 ft (5.5 m) to accommodate the taxiway. The other bridge will cross a vehicle access road and the existing PHX Sky Train® automated people mover, which opened in 2022. The access roadways and the automated people mover will remain in operation for the full duration of construction.

The bridges are designed for Federal Aviation Administration (FAA) Airplane Design Group (ADG) VI gravity loading, controlled by the Airbus A380 airplane. Current FAA guidance on the design of bridges carrying aircraft loading is limited to a few bullet points and a reference to AASHTO’s Load and Resistance Factor Design 7th Edition. In addition to these two documents, the American Concrete Institute (ACI) has published ACI 343R-95: Analysis and Design of Reinforced Concrete Bridge Structures, which includes a section on airport bridge loads; however, this document was last updated in 2004. This leaves much of the live load application methodology up to the designer. This paper will explore these challenges and discuss our team’s solutions.

Project Overview

Sky Harbor International Airport, located in Phoenix, Arizona, services over 400,000 takeoffs and landings each year[1]. With such a large amount of air traffic, the airport has identified several expansion projects to improve maneuverability and aircraft queue timing. Included is the construction of a new cross-field taxiway – Taxiway U. The airport has both north and south airfields, separated by the terminals and the airport's main entrance roadways. The new taxiway will connect these airfields by spanning the entrance roads and other obstructions, such as utilities and airside service roads. See Figure 1 for the proposed layout of Taxiway U.

Figure 1. Proposed Taxiway U Layout



The north and south airfields are currently at approximately the same elevation as the airport entrance roads, Sky Harbor Boulevard and Buckeye Road. Due to the maximum 1.5% taxiway grade set by the Federal Aviation Administration (FAA)[2], it is not feasible to raise the taxiway to a sufficient elevation to clear these roadways. As such, the roadways will be lowered by approximately 18' (5.5 m) to provide the required vertical clearance for both taxiways. In addition to the bridge carrying Taxiway U over the entrance roads, a second bridge is required to span the PHX Sky Train© and a South Vehicle Service Road (VSR). The PHX Sky Train© is an automated people mover (APM) designed to carry airport passengers from the terminals to parking lots, rental car facilities, and local transit. Phase 2 of the PHX Sky Train© opened on December 20, 2022.

In addition to the two taxiway bridges, this project includes 14 retaining walls to support the new taxiway and facilitate the lowering of the airport access roads. Gannett Fleming is leading design development and program support services for the new taxiway, including structural design of the bridges and retaining walls. The bridge construction is scheduled to start in late summer 2024 and be completed in spring 2027.

Interdisciplinary Coordination

Effective coordination between disciplines is essential to the success of this project. Project disciplines include site development for parking lot relocations, roadway design for the realignment of the airport access roads and service roads, aviation design for the design of the taxiway, and utilities, drainage, and electrical design. Additionally, the project will require the retrofit of several cargo buildings, necessitating structural building design as well.

This project will require multiple utility relocations, including several large power duct banks that supply power to the PHX Sky Train©. Additionally, because the roadways are being depressed, proper stormwater management is paramount, and a pump station will be required. Figure 2 shows a rendering of the proposed new taxiway.

Figure 2. Rendering of Proposed Taxiway U

Phasing and Project Delivery

Because this project realigns the main entrance roadways to the airport, construction phasing/staging is critical. Sky Harbor Boulevard, Buckeye Road, and a facilities access road must remain open throughout the duration of the project. In order to mitigate the risk that comes with this challenge, the City of Phoenix Aviation Department has chosen to deliver this project via Construction Manager at Risk (CMAR). This delivery method suits this project very well as it offers a means to work out construction impacts and detailed cost and schedule models during design, prior to the onset of what will be impactful construction to airport operations. Preconstruction work jointly performed by the CMAR, Designer, and Owner is critical to confirm schedule, costs, planning, and impacts to traffic and airport operations. Additionally, keeping the enabling work (Facilities and Services modifications and Air Cargo modifications) and taxiway work all under one CMAR allows for improved schedule and phasing management between enabling work and the taxiway work.

Design Criteria

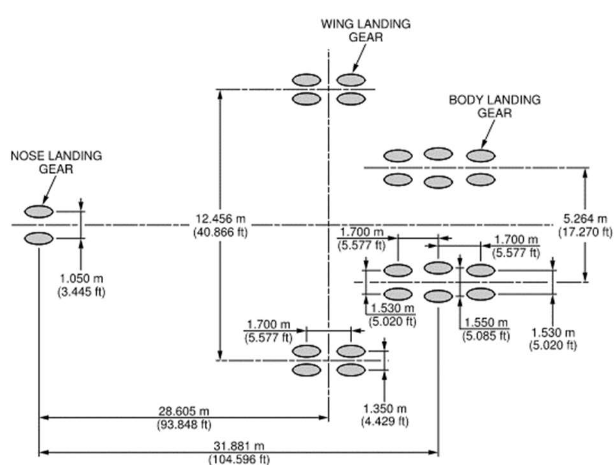
Although there are few design guidelines for structures that carry airplanes, FAA Advisory Circular (AC) 150/5300-13B includes information on required geometrics[2] and FAA AC 150/5320-6G indicates that structures should be designed per American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 7th Edition[3,4]. The design was therefore carried out in accordance with this document as appropriate, including load factors and combinations.

According to FAA AC 150/5300-13B, bridges should be designed for the heaviest aircraft expected to use them. The FAA has created Airplane Design Groups (ADG) I through VI based on tail height and wingspan. These groups dictate both loading and geometrics. For this project, the City of Phoenix Aviation Department has determined that the loading shall be based on Group VI, which includes the Boeing 747 and Airbus A380, but that the geometrics shall be based on Group V, which includes aircraft with up-to a 214’ (65.2 m) wingspan. FAA AC 150/5300-13B states that the width of any taxiway must never be less than the taxiway safety area (TSA), which is 214’ (65.2 m) for a Group V design group. The bridges on this project are therefore designed to accommodate the 214’ (65.2 m) wide TSA.

Additionally, the American Concrete Institute (ACI) has published ACI 343R-95(04), Analysis and Design of Concrete Bridge Structures, which has a section on airport runway bridge loadings[5]. This section discusses both runway and taxiway bridges. The section is small and much of the information is superseded by the FAA documents, AASHTO, or the Aircraft Characteristics manual (discussed further below).

In order to facilitate airport improvements around the globe, aircraft manufacturers publish Aircraft Characteristics manuals that include aircraft geometry and loading. For both the Boeing 747 and Airbus A380, these manuals were used to determine the vehicular live load on these bridges. The maximum pavement weights were compared, and it was determined that the controlling aircraft load is the Airbus A380. The total pavement weight of the Airbus A380 is approximately 1272 kips (5658 kN), with most of the weight carried by the wing and body landing gear[6]. In addition to the vertical loading, the aircraft imparts a design braking force of 0.8g to the bridge (i.e. 80% of the vertical load). See Figure 3 for the Airbus A380 landing gear footprint.

Figure 3. Airbus A380 Landing Gear Footprint



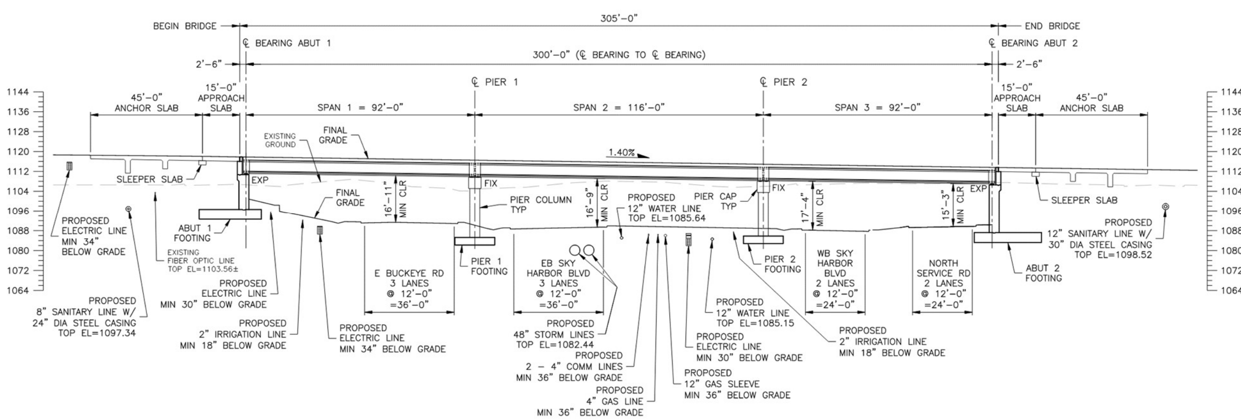
Source: Airbus A380 Aircraft Characteristics - Airport and Maintenance Planning

A dynamic load allowance was applied to the static vertical live loads, in order to account for wheel load impact from the moving aircraft. ACI 343R-95(04) recommends an impact value of 30% for parking aprons and low-speed taxiways, 40% for high-speed taxiways and runways, and 100% for touch-down areas of runways. Taxiway U will be considered a low-speed taxiway. For the North Bridge, which will be directly exposed to aircraft loading, a value of 33% was adopted, which matches the AASHTO LRFD dynamic load allowance requirement. The dynamic load allowance was reduced for the South Bridge since aircraft loads are applied through a layer of fill atop the structure. ACI 343R-95(04) recommends that impact from low-speed taxiway aircraft loading for structures covered with fill varies proportionally from 30% for no fill to 0% for 10’ of fill. As such, the impact factor used for this bridge is 12%.

Bridge over Sky Harbor Boulevard and Buckeye Road (North Bridge)

This bridge will carry Taxiway U over Sky Harbor Boulevard and Buckeye Road, as well as an airside service road. Once constructed, the bridge will be 300’ (91.4 m) in length, with end spans of 92’ (28.0 m) and a centre span of 116’ (35.4 m). This span configuration allows space for the roadways, as well as sub-surface utility corridors between the substructures and outside of the paved roadway areas, to facilitate future access to the utilities for future maintenance and development work. The elevation view of this bridge is shown in Figure 4.

Figure 4. Elevation View of the Proposed North Bridge



<u>Structure Type</u>

At Sky Harbor International Airport, several taxiway bridges already exist as precedent. Taxiways S, T, and R cross over Sky Harbor Boulevard east of the proposed Taxiway U alignment, on cast-in-place reinforced and post-tensioned concrete slab bridges. Early in the design process, it was determined that this structure type would not be compatible with the planned span-by-span construction phasing (see “Construction Sequence” section below), and that a precast prestressed concrete girder type would be preferred for this bridge. Steel girders were similarly not considered, due to cost.

Several configurations of precast prestressed concrete girders were assessed for feasibility and sizing during the preliminary design phase. This includes the following girder types in various depths and spacings:

- Bulb tee (Utah DOT standard shapes)
- Side-by-side box girders
- Spread box girders
- U-shape/tub girders

Keeping the superstructure depth to a minimum was a key consideration in the selection of the structure type, due to the cost of the excavation and drainage improvements associated with lowering the roadways. Furthermore, the vertical profile of the new taxiway is constrained by the 1.5% maximum grade and the elevation of the existing taxiways to the north and south.

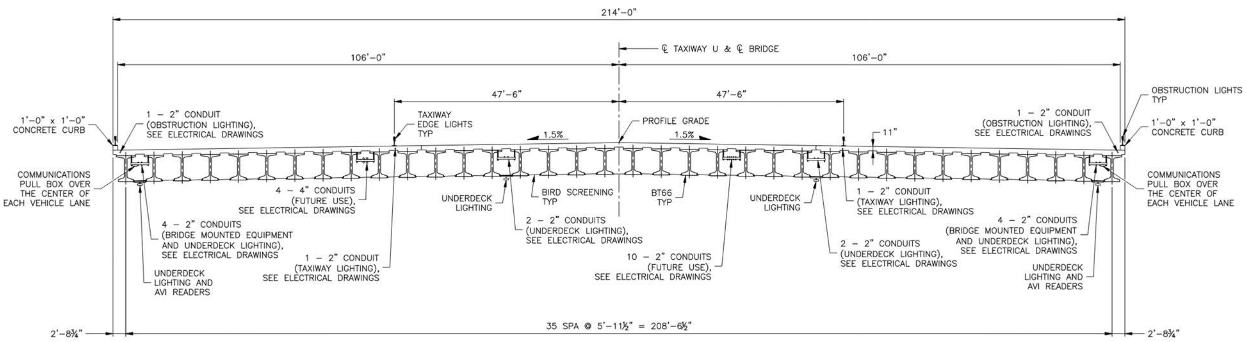
In addition, the City of Phoenix Aviation Department expressed a preference for a structure configuration which would not provide areas for birds to nest, an important operational concern for the airport. Therefore, all of the girder types other than side-by-side box girders would require bird exclusion screening to be installed, such that birds cannot enter the space between girders.

Construction costs for each of the feasible options were estimated by the CMAR and it was determined that 66” (1676 mm) deep Utah bulb tee girders (UBT-66) would be the most economical girder type, including consideration of the additional costs for bird exclusion screening. Supports for the bird screening will be incorporated into the girder design, embedded in the bottom flanges.

The new bridge will be made continuous for live load with a continuous composite deck slab and continuity diaphragms, in order to improve structural efficiency and thereby minimize the girder depth, as well as to avoid the need for expansion joints at piers. The proposed span lengths were selected to balance the structural demand as evenly as possible between spans.

The bridge deck will be 11” (279 mm) thick, with the deck thickness controlled by punching shear requirements. Steel-reinforced elastomeric bearings will support the girders at piers and abutments, with steel cable restrainers providing fixity at the piers. Each pier consists of 16 circular columns of 4’ (1.2 m) diameter, supporting a pier cap. Strip seal expansion joints will accommodate movements and rotations at the abutments. The piers and abutments will be supported by spread footing foundations. See Figure 5 for the bridge typical section.

Figure 5. Typical Section of the Proposed North Bridge

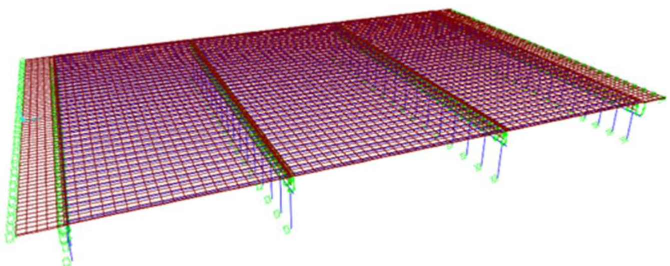


Taxiway edge lighting and obstruction lighting will be embedded in the deck slab, to meet taxiway lighting requirements. In addition, underdeck lighting and automatic vehicle identification equipment will be supported from the girders, to service the roadways below the bridge. Conduits will be supported between the girders to service the lighting and equipment, and several additional conduits will also be provided for future power and communications utilities.

Design Methodology

The global behaviour of the structure was analyzed in CSiBridge as shown in Figure 6. The deck and diaphragms are modeled using shell elements and the girders and substructures are represented by frame elements, with link elements representing the bearings.

Figure 6. CSiBridge Model



By default, CSiBridge uses influence-based analysis for moving loads, with influence surfaces computed and concentrated loads multiplied by the influence value at the point of application to obtain the corresponding response. If the design lane is wider than the design vehicle, the software moves the load transversely across the lane to capture the most severe response. The load at each longitudinal location in the vehicle is independently moved across the width of the lane, and therefore the front and rear axles of a vehicle may not be placed at an accurate transverse location in the lane relative to one another, when placed for maximum effect. For a typical design vehicle, with all axles sharing the same axle width, any resulting overestimation of the response is typically negligible.

For the aircraft loading used on this project, we found that running the design aircraft live load in an influence-based analysis as described above resulted in a significant overestimation of the girder response, particularly for the exterior girders. This is because the software was moving each axle transversely across the bridge independently from the other axles, resulting in a single girder being subjected to both the body and wing landing gear simultaneously. However, in the actual landing gear footprint, the body landing gear is offset transversely from the wing landing gear, meaning the wing landing gear would be located over a different girder than the body landing gear. Since live loading comprises such a large proportion of the total loading, transverse distribution of live load effects has a significant effect on the girder sizing and design. To accurately analyze the live load effects, we instead created multi-step static cases in CSiBridge, with the live load run over the bridge at several transverse offsets to capture the most severe response.

Figure 7. A380 Wheel Load Layout in CSiBridge

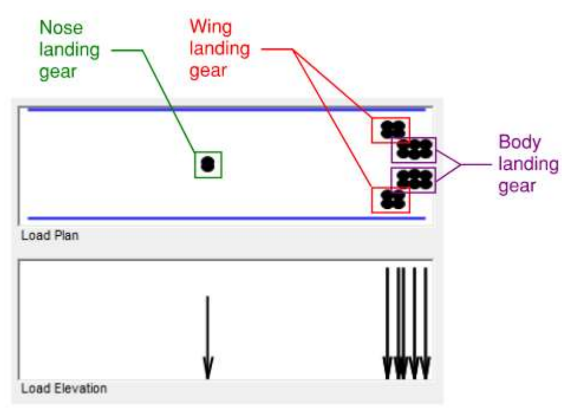


Figure 8. Comparison of Mid-Span Moments for the Different Live Load Analysis Methods

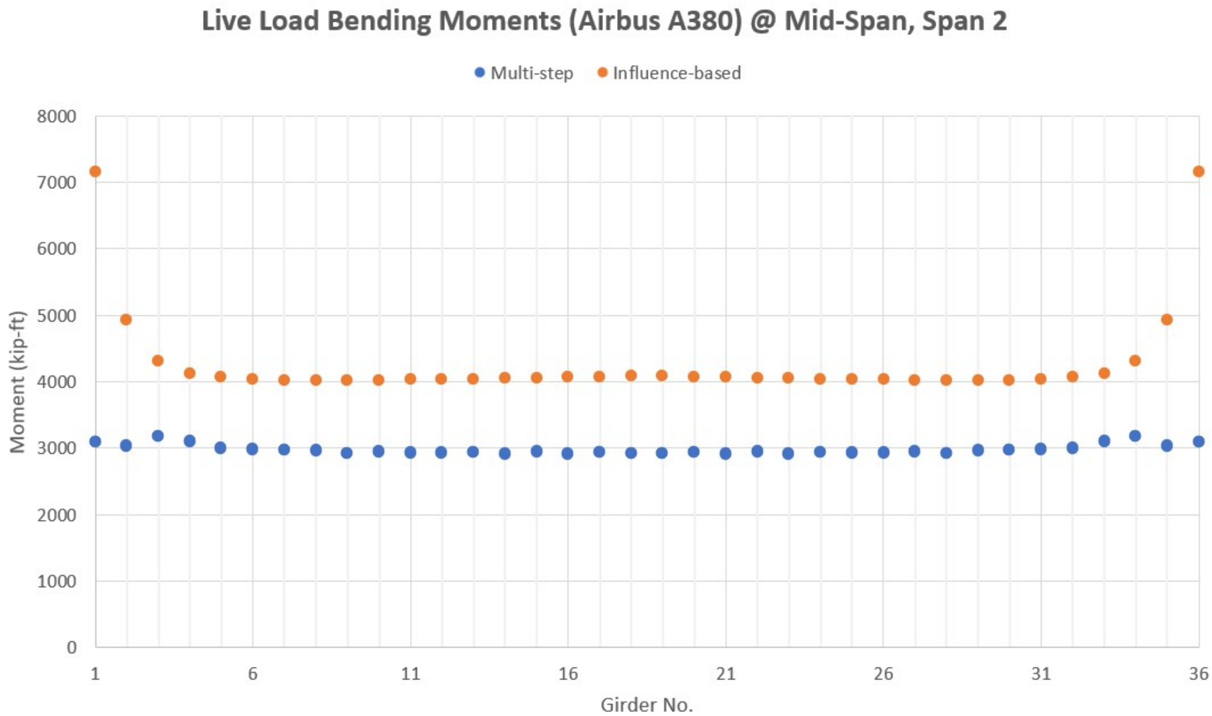
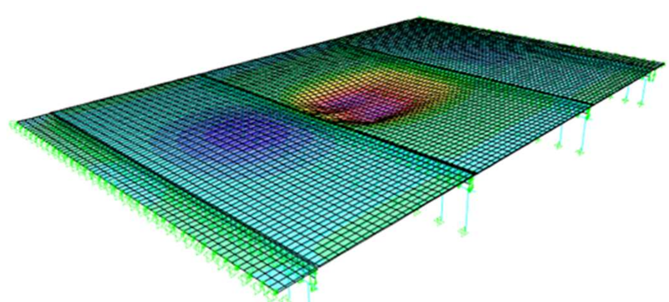


Figure 8 shows a comparison of bending moments at mid-span of the centre span for the multi-step and influence-based live load analysis methods under Airbus A380 loading. As shown in this figure, the multi-step analysis results indicate that the two exterior girders are subjected to slightly lower bending moments than the third girder, since the outer girders are only subjected to the wing landing gear and not the heavier body landing gear. Figure 9 shows the deformed shape under vertical live load, with the body and wing landing gear of the design aircraft located over the centre span.

Figure 9. CSiBridge Model Showing Deformed Shape (exaggerated) due to the Airbus A380 Loading



Based on the live load analysis results from the CSiBridge model described above, live load distribution factors were calculated, and LEAP Bridge Concrete (part of Bentley OpenBridge Designer) was used for the design of the precast/prestressed concrete girders. For the design of substructure elements and bearings, responses were obtained from the CSiBridge model.

Longitudinal braking forces, equivalent to 80% of the gravity loads, applied to the deck are transferred to the piers, which are designed accordingly. At abutments, 15’ (4.6 m) long approach slabs are provided, including connection to the abutment backwall. For the design of the abutments, consideration was given to the aircraft live load surcharge, but also the possibility of longitudinal braking forces being applied to the approach slabs and transferred to the abutment backwall.

Construction Sequence

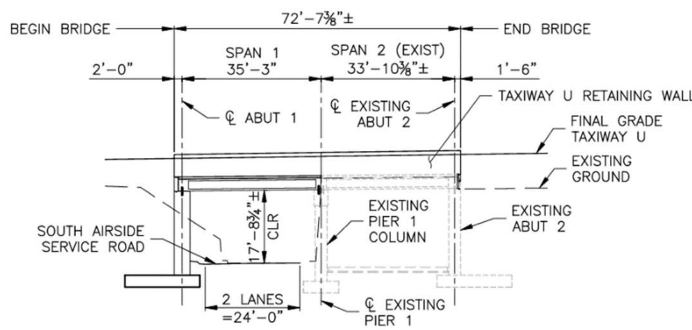
In order to maintain operation of Sky Harbor Boulevard and Buckeye Road during construction of the bridge and lowering of the roadways, each of the three spans will be constructed independently. The deck slab of the centre span will be poured before erecting the girders of the end spans, and the deck reinforcement is detailed accordingly. After the girders of adjacent spans are in place and the deck slab within these spans has been poured, transverse closure pours will be carried out to establish continuity. Stay-in-place metal forms will be utilized for the deck slab, to eliminate the need for stripping forms from the relatively tight spaces between girders.

Bridge over PHX Sky Train© and South Vehicle Service Road (South Bridge)

This bridge spans the PHX Sky Train© and South VSR at the south end of the project. This bridge is located entirely within the "airside" portion of the airport (i.e. not accessible by the general public). The span over the PHX Sky Train© was built as part of the Sky Train© project, as the airport anticipated the future construction of Taxiway U and aimed to avoid disrupting its operations with this future expansion. The Taxiway U project will include construction of the span over the South VSR, as well as the taxiway atop the structure. Figure 10 shows the elevation view of this bridge.

The existing span was designed using the AASHTO Standard Specifications for Bridge Design (17th Edition). For consistency, the proposed span will utilize the same criteria.

Figure 10. Elevation View of the Proposed South Bridge



When the City of Phoenix Aviation Department was initially considering the construction of Taxiway U, they planned for the geometry of Taxiway U to accommodate Group VI aircraft. As such, the existing Taxiway U span is 262' (79.86 m) out-to-out. The proposed span geometrics are designed for Group V; therefore, the second span will be slightly wider than the required 214' (65.23 m) Group V width. The taxiway centerline alignment will be 107' (32.61 m) from the left edge of the existing deck.

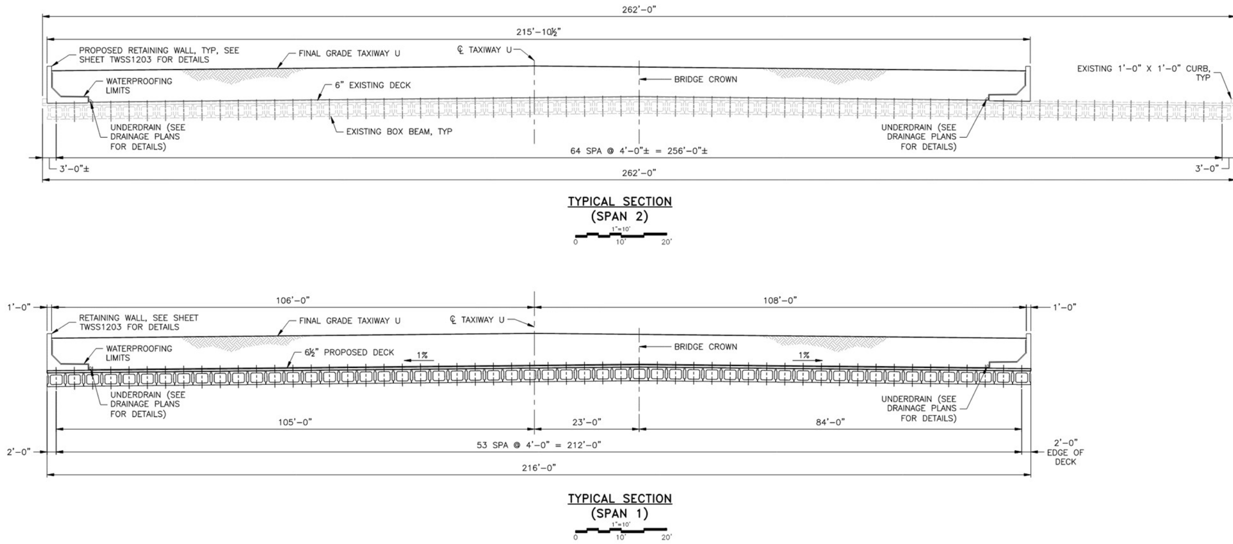
Structure Type

The existing span is 34’ (10.36 m) long and utilizes 65 side-by-side precast prestressed concrete box girders. The deck thickness is 6” (152 mm) and there are 12” x 12” (305 mm x 305 mm) curbs along each edge of deck. The existing span has a normal crown, with the high point centred within the 262’ (79.86 m) out-to-out width. A photo of the existing structure is provided in Figure 11.

Figure 11. Existing Span over PHX Sky Train©

The South VSR is being reconstructed as a part of this project, but its profile will remain approximately the same as existing. Consequently, increasing the superstructure depth for the proposed span while maintaining minimum vertical clearance was not possible. Therefore, the proposed span will utilize a similar configuration to the existing, with a span length of 34’ (10.36 m) and 54 side-by-side box girders, also with a 6” (152 mm) deck. This yields an out-to-out width of 216’ (65.84 m). The proposed span cross-slope will match the existing span, meaning that the high point will be 130’ (39.62 m) from the left edge of deck. Figure 12 shows the typical sections of both the existing and proposed spans.

Figure 12. South Bridge Typical Sections



When the existing span was designed, the actual profile of the taxiway was unknown; and therefore, the deck elevation was set low to accommodate a range of possible taxiway profiles, with the understanding that fill could be placed on top of the bridge to attain the actual taxiway profile. The designers of the existing span assumed that up to 10' (3.05 m) of fill could be placed above the deck surface. The actual fill depth is approximately 6' (1.83 m) and varies both longitudinally and transversely to provide for the difference between the taxiway grade and bridge deck grade, and the taxiway's cross-slope. Cantilever retaining walls at the left edge of deck and at 214' (65.23 m) from the left edge of deck will be used to retain the fill.

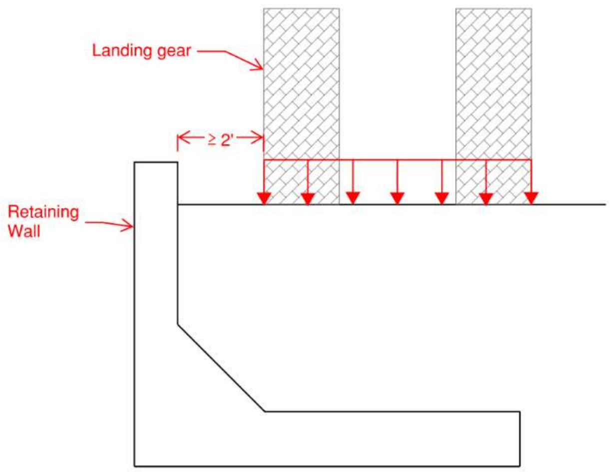
Because of the fill depth, there is not a significant differential in subgrade stiffness between the bridge and surrounding grade, and therefore approach slabs are not required for this structure. Both spans will behave as simple spans, with the boxes supported by elastomeric bearing pads and a doweled connection between the abutments and pier cap through the girder end diaphragm.

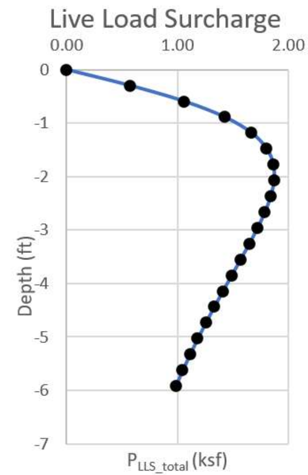
Retaining Walls on Bridge

Per the FAA, the entire 214' (65.23 m) taxiway surface must be designed for the weight of the controlling aircraft; thus, it must be assumed that the landing gear axles could be placed adjacent to the retaining wall. The AASHTO-prescribed two-foot live load surcharge does not accurately represent the weight of the airplane's landing gear and would not be appropriate for the design of these retaining walls.

It would not be possible for the body landing gear to approach the edge of pavement without the wing gear falling off the edge of the deck, so the controlling loading will be the wing landing gear. The outermost edge of the wing landing gear was placed 2' (0.61 m) from the face of curb, per AASHTO. The load from all four tires was converted to an area load over the area bounded by the outline of the four tires. This yielded a distributed load of 3.22 ksf (154 kPa). The lateral pressure on the wall was determined using a Boussinesq distribution. It was also verified that the effect of the body landing gear would be negligible based on its distance from the wall. The loaded area and resulting Boussinesq distribution are presented in Figure 13.

Figure 13. Wing Landing Gear Footprint & Lateral Loading due to Boussinesq Distribution



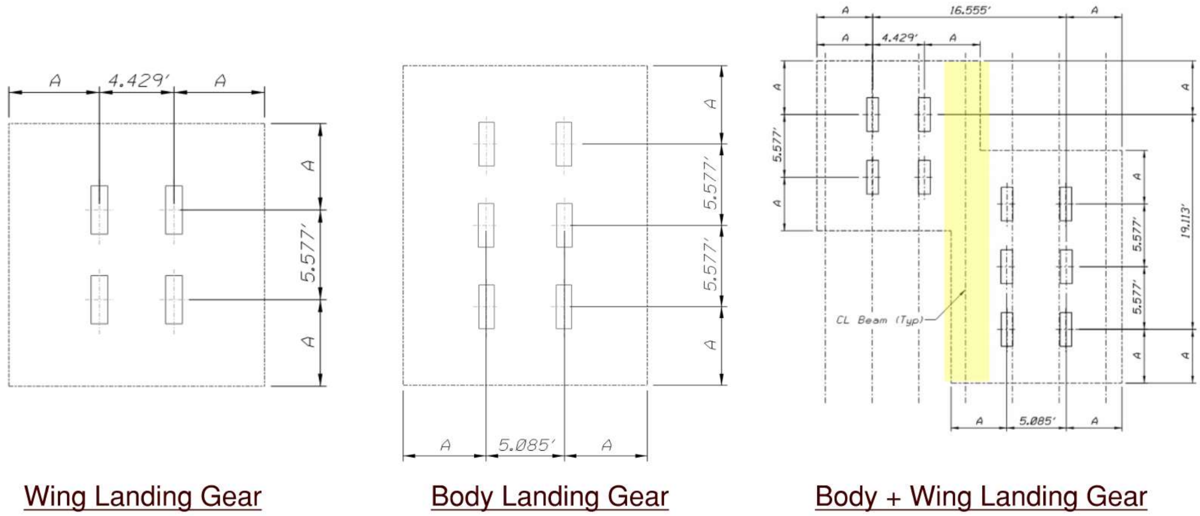


In order to minimize work over the PHX Sky Train© and thereby avoid impacting its operations during construction, these walls will be precast. The average length of each precast unit is approximately 9'-1" (2.77 m), with cast-in-place closure strips between units to them together. A portion of the footing heel is also cast-in-place. Dowels will be installed into the deck slab within the cast-in-place portion of the heel, to anchor the wall to the slab.

Girder Design

The aircraft loading is applied to the girders through approximately 6' of fill. The distribution of the wheel loads through the fill was considered per the AASHTO Standard Specification, which states that for fill depths exceeding 2' (0.61 m), point loads can be distributed over a square with sides equal to 1.75 times the fill height, and the load at overlapping areas need not be increased[7]. The wheel load distribution areas are shown in Figure 14, with A equal to 0.875 times the fill height. The "Body + Wing Landing Gear" case governs the girder design since a girder can be loaded by both sets of landing gear simultaneously according to this distribution. The nose landing gear was ignored due to the relatively short spans.

Figure 14. Wheel Load Distribution Through Fill



The existing girder design was found to be sufficient to carry the actual loads using this project's parameters. Had the girders not passed this design check, a more robust investigation into the live load application and distribution would have been required.

Retaining Walls

The project includes 14 retaining walls, to support the new taxiway and facilitate the lowering of the airport access roads. For seven of the walls, standard reinforced concrete cantilever retaining wall designs published by the Arizona Department of Transportation (ADOT) were utilized. The remainder required additional consideration:

- Two walls are soldier pile and timber lagging walls, with a permanent cast-in-place concrete facing, where excavation was limited due to site constraints.
- One wall ties into an existing wall and requires the use of a moment slab over the existing and proposed walls to maintain the existing barrier location.
- Three walls are subjected to aircraft surcharge loading behind the wall.
- One wall exceeds the 30' (9.14 m) maximum height for use of standard ADOT designs.

The retaining walls subjected to aircraft loading were designed for the landing gear surcharge loading based on a Boussinesq distribution, similar to the retaining walls on the South Bridge as described above. Form liners will be utilized to apply a rustication pattern to all walls in public-facing areas.

Conclusion

In conclusion, the approach to the design of structures supporting aircraft with complex phasing is necessarily distinct from the design of roadway and railway structures, particularly with regards to the application of aircraft live loads and consideration of geometric requirements. For the Taxiway U project, addressing these specific challenges was essential for achieving a design that is cost-effective, constructible, and safe.

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