Concrete Segmental Bridges—
Preliminary Design Approximations for Span Layouts and Structure Depths

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This article discusses preliminary design approximations for span layouts and longitudinal structure depths for concrete segmental box-girder bridges. Strictly speaking, these approximations apply to concrete segmental bridges. However, they are useful approximations for all post-tensioned concrete bridges. Note that the recommendations presented here may not apply to some bridge designs. For example, designs outside of the recommended ranges can occur when span layouts must take into account obstructions below the bridge, or when structure depths are constrained by clearances and profile grade. However, these recommendations typically result in optimal designs.

Why are design approximations used? A starting point is necessary before proceeding to final design. In final design, the structure will be analyzed in detail and address the following matters:

- Time-dependent time-step analyses, both longitudinally and transversely
- Shear, torsion, and moment designs for the service and strength limit states
- Special element design for diaphragms, deviators, anchor blocks, and other elements

These detailed analyses and designs will vet the preliminary design and provide the exact amount of concrete, post-tensioning, and reinforcement required. Using final-design level of effort and analyses in preliminary design would be costly in both schedule and engineering hours. And while a final design without a high-quality preliminary design may meet all the required structural design specifications, it may not be the optimal solution for the project. Using proven preliminary design approximations, along with experience, provides a greater probability of reaching an optimal solution in terms of design and constructability.

The first step in preliminary design is determining an optimal span layout. Substructure units and foundations must avoid streets, navigation channels, buildings, and other obstacles. Sometimes, these obstructions play a large part in determining the span layouts and there is little room for variation. However, what spans should be used when there is more of a "blank canvas"?

The cost of the substructure units helps determine what span lengths to use. When substructures are relatively inexpensive, shorter spans are typically chosen. Examples of this situation include urban viaducts with short piers or shallow water crossings with good site access. For concrete segmental bridges, the span-by-span erection method is typically the least-expensive erection method for shorter spans. Span-by-span erection has been used in spans up to 180 ft. However, it is most efficient and economical for spans in the 100- to 150-ft range.

The cost of the substructure is greater when a bridge crosses deep water, deep canyons, rugged terrain, or spans obstacles such as navigable channels. For concrete segmental bridges, the longer span lengths associated with challenging site conditions or relatively expensive substructure units can push the erection method to the balanced-cantilever erection method. Precast concrete balanced-cantilever erection has typically been used for spans ranging from 180 to 450 ft, although longer spans have been used for some projects. Precast concrete segments can typically be transported on highway and road systems when their weight is 50 tons or less and there are adequate clearances for the segments along the proposed route. Beyond this weight, a detailed investigation of the route, including bridge capacities, must be performed to verify the feasibility of transportation options. Much larger segments can be transported by barges; in such cases, the casting yard and erection site equipment typically govern the segment weights.

Cast-in-place (CIP) concrete balanced-cantilever design is typically used for spans ranging from 300 to 600 ft, although, again, there are exceptions. CIP concrete segments may be chosen if the transportation route and/or equipment capacities indicate that precast concrete segments are not practical. Site constraints on crane placement can also make CIP balanced-cantilever construction the preferred alternative.

Span layouts for span-by-span erection strive to use uniform span lengths. This strategy aids in the design and operation of erection trusses or gantries. To simplify erection equipment needs and operations, it is optimal for the end spans to be approximately the same length as the interior spans (**Fig. 1**). The reduced post-tensioning secondary moments in end spans help offset the increased permanent and live-load moments. The secondary moments in end spans are less than those in interior spans because there is no rotation restraint at the expansion joint. The secondary moments are zero at the expansion joint and increase across the span to the first interior pier. Therefore, near midspan, the secondary moments are about half of the secondary moments for interior spans.

Bridges erected span by span are almost always constant depth with a span-to-depth ratio kept within the range of 16

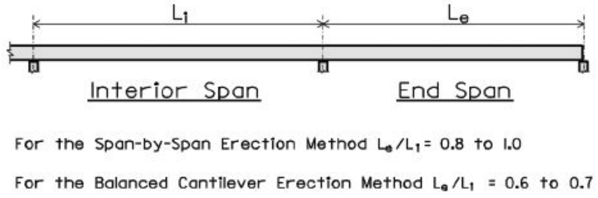


Figure 1. Ratios of end-span length to interior-span length for preliminary span layout. All Figures: R. Kent Montgomery.

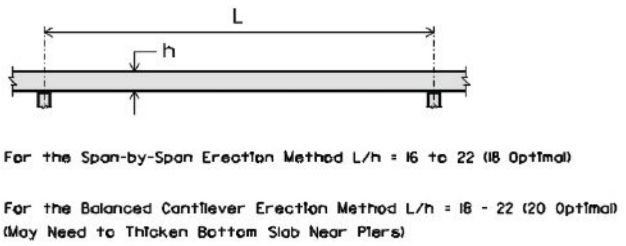


Figure 2. Optimal structure depths for constant-depth concrete segmental bridges.

to 22, with 18 being optimal (**Fig. 2**). A minimum depth of approximately 7 ft should be used to provide reasonable access inside the box girder during construction operations as well as post-construction inspection and maintenance activities.

For balanced-cantilever erection, the end spans are typically set shorter than the structural optimum as a constructability consideration. A typical cantilever extends approximately one-half of the interior span length. For end spans, the portion of the span between the end of the cantilever and the abutment/pier must be erected by other means, typically on falsework. However, uplift at the end of a unit should be avoided. For the previously cited reasons, end spans are typically set at lengths of between 0.60 and 0.70 of an interior span length (Fig. 1).

Variable-depth structures add complexity and cost. Therefore, for spans erected by the balanced-cantilever method with span lengths less than approximately 250 ft, designers typically use constant-depth spans with a span-to-depth ratio of 18 to 22, with 20 being optimal (Fig. 2). The bottom slab will typically require thickening to resist the cantilever moments. This objective can be accomplished by thickening to the inside of the box girder, or with a small thickening to the outside over a short distance.

As spans increase to more than 250 ft, variable-depth spans become more economical. The span-to-depth ratio at piers is usually kept between 18 and 22, with 20 being optimal. The span-to-depth ratio at midspan is typically kept between 35 and 50, with 45 being optimal (**Fig. 3**). The guideline for midspan depth also applies for end spans near an abutment or expansion pier, with the same minimum depth of approximately 7 ft recommended for access. For variable-depth structures, the variation in depth along the span must be defined. This curve is typically referred to as the intrados. During preliminary design, a simple equation (**Fig. 4**) that provides flexibility can be used to define the depth variation along the span.

$$h = h_o + Cx^n$$

where

C = constant depending on the cantilever length and depths at pier and midspan
$= (h_p - h_o)/(L_c)^n$
h = depth at distance x (typically measured from the edge of the midspan closure joint to the face of the pier diaphragm)
h_o = depth at midspan
h_p = depth at piers
L_c = cantilever length (typically from midspan to the piers)
n = exponent controlling the profile
x = distance along the span (typically measured from the edge of the midspan closure joint to the face of the pier diaphragm)

The exponent n is typically set between 1.70 and 1.90, with 1.75 to 1.80 being optimal. Increasing the exponent toward the upper limit can aid in providing vertical clearances for navigational channels or other required clearances. However, increasing the exponent to more than 1.90 (approaching a parabola) results in a critical region near the quarter span (mid-cantilever) that will govern the design above other regions in the span/cantilever. This configuration can require added cantilever post-tensioning for the critical region, as well as an increased tendon size for all cantilever tendons whose anchorages are beyond the critical region. This configuration can also require increased web widths to control principal tension in the critical region, although the increased web widths would not be required elsewhere.

Figure 3. Structure depths for variable-depth concrete segmental bridges.

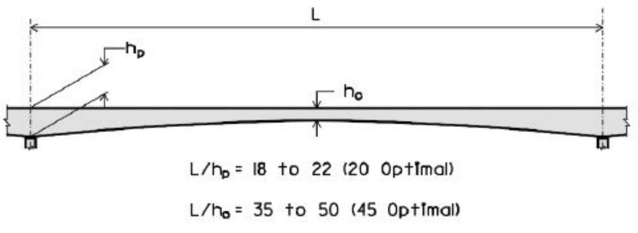
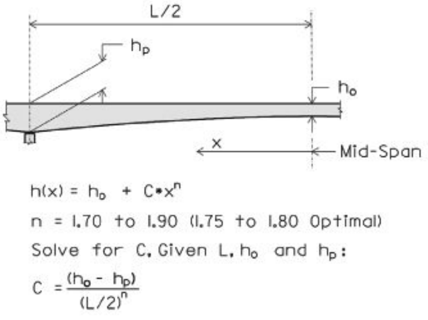


Figure 4. Intrados definition. Variation in depth along the span (intrados) for a variable-depth concrete segmental bridge.



If the exponent is set to less than 1.70 (a flatter curve), the self-weight of the cantilever increases, and the section near the pier will govern the design above other regions and will require an increased amount of cantilever post-tensioning. If the exponent is set optimally, each region (as represented by the model node at each segment joint) will be close to governing equally, both for cantilever and long-term moments along with shear.

The bottom slab will need to be thickened near the pier to control compression stresses and provide adequate negative-moment capacity. The thickness will depend on the span length and intrados selected. At the piers, a good rule of thumb is to provide 9 in. of thickness for every 100 ft of span length. Using this initial bottom-slab thickness at the pier, simple cantilever calculations can be performed by hand or using a spreadsheet to iterate to a final thickness, as follows:

1. Calculate the cantilever moment during construction and determine the amount of cantilever post-tensioning to limit the top tension stress to zero (precast concrete), or $0.0948\sqrt{f_c'}$ ksi (CIP concrete with continuous reinforcement).
2. Check the bottom compression stresses to determine whether they are within the limiting compressive stress. If the compressive stresses are outside the limit, increase the thickness of the bottom slab; if they are significantly less than the limit, decrease the thickness. If the thickness is adjusted, repeat steps 1 and 2.
3. Calculate the neutral axis location for the negative moment at the strength limit state to ensure that the axis is not located significantly above the bottom slab, which could result in a flanged section with less-ductile behavior. If required, thicken the bottom slab and repeat steps 1 through 3.

Note that the bottom thickness is sized for the cantilever state during construction, and calculations should account for any construction equipment load on the cantilever (such as beam and winch or form travelers), as well as 10 lb/ft^2 of general construction live load across the deck area. The 10 lb/ft^2 is required by Article 5.12.5.3 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] and accounts for miscellaneous construction loadings such as strand packs, reinforcing bars, portable toilets, or personnel. If there is significant construction equipment on the cantilever, the cantilever state during construction should govern over the in-service state of the structure with live load included. If the only load applied to the cantilever is the additional 10 lb/ft^2 general construction live load (that is, no significant construction equipment is considered), the cantilever state and in-service state should be close to governing equally. Minor adjustment to the bottom-slab thickness at the pier may be needed during final design. The bottom-slab thickness typically varies from maximum at the pier to the minimum thickness across a length, which is equal to approximately 30% of the span length. This variation can be linear or curved using the same exponent as for the structure depth variation (intrados).

Preliminary design involves still more effort to determine the remainder of the cross-sectional segment dimensions. The amount of continuity post-tensioning and anchorage locations must be determined, as well as the articulation (pier types, fixity, and location of expansion joints). However, good span layouts and structure depths provide the first steps in a quality preliminary design. Addressing these aspects of design in the early stage will result in minimal changes during final design, which is essential for an efficient final design process.

Reference

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.

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