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Comparative Analysis of Bridge Abutment Types

David Fell
daf60@uakron.edu

Selecting a Substructure

A Comparative Analysis of Bridge Abutment Types

David Fell

Williams Honors College, University of Akron

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Abstract

This project was developed to serve as a brief overview of design practices and considerations in the selection of highway bridge abutment types. This involved a review of literature in the form of reviewing national design guides and department of transportation (DOT) requirements from both US DOTs and international DOTs. The abutment types covered in this research included conventional reinforced concrete abutments with bearings, integral abutments, and semi-integral abutments. This research focused solely on highway bridge abutments, particularly on Ohio Department of Transportation design requirements due to their extensive use of semi-integral abutments. Superstructure elements and geometric requirements are primary drivers for abutment selection and those relationships are explored.

Introduction

Bridge design is a crucial part of civil engineering and infrastructure. Bridge design is particularly challenging because of the intersection between structural, geotechnical, and roadway engineering. Like most engineering problems, there is rarely a perfect solution to a given bridge design issue. Bridge engineers must manage the tradeoffs and benefits associated with the decisions of each design element. They must balance cost efficacy of design with safety and reliability of the structure. The design components for a bridge can broadly be categorized as superstructure and substructure. Superstructure elements include the bridge deck, the parapet, the beams and/or girders, and any frames or bracing between the beams and/or girders. The superstructure supports loads from traffic or other loads on the deck or railing. These loads are predominantly vertical, but there are also lateral loads such as wind loads. The superstructure can also experience loads longitudinally, or along the centerline of the bridge. Braking and traction forces travel along the beams of the structure, as well as large thermal loads. The superstructure transfers these loads to the substructure elements, which in turn transfer them to the earth through foundations.

Substructure elements on bridges generally include abutments and piers. Substructure elements carry the vertical and horizontal loads from the superstructure and transfer them to their foundations. Abutments are located at the beginning and ends of a bridge, while piers provide intermediate support to the superstructure between the abutments. In addition to the loads from the superstructure, abutments also experience soil loads from the backfill behind them and surcharge loads on top of the backfill. Bridge engineers must carefully understand these loads and their effects. Selecting an abutment type is critical to the longevity, serviceability, and cost of a bridge. Three common abutment types are conventional abutments featuring supporting bearings, integral abutments with girders cast into the backwall, and semi-integral abutments with a combination of both. Each abutment type has its own unique set of advantages and disadvantages, and the onus is on engineers and departments of transportation (DOTs) to understand the applicability of each abutment type. Efforts have been made to thoroughly investigate the behavior of abutments in the short and long term, and those efforts have been summarized.

Conventional Abutments

Conventional abutments can broadly be categorized as stub or tall. Stub abutments are typically used in areas where embankment below the bridge is possible. Stub abutments typically retain only the approach fill and are used in areas where horizontal clearance between the abutment face and any water or travel way is not a major concern. However, stub abutments can be used in combination with other retaining walls, such as mechanically stabilized earth (MSE) walls. Stub abutments used in combination must be supported on deep foundations instead of spread footings (ODOT, 2022). The designs of the retaining wall and the abutment must be checked for potential interferences between the two. The abutment will exert some amount of surcharge load on the wall (Coletti, 2022). The other type of conventional abutment, a tall abutment, can be used in areas where horizontal clearance is an issue, as they are designed to function as both a retaining wall and an abutment. Figure 1 in the Appendix shows the ODOT standard drawing for a conventional stub abutment.

Conventional abutments feature a distinct separation between substructure and superstructure elements. The substructure and superstructure do interact; however, it is facilitated through bearings and expansion joints. The bearings in a conventional abutment include their own complex design procedure and practices, which are outside the scope of this paper. Bearings can generally be categorized as expansion or fixed, and the type of bearing used on the abutment will factor into the design. Bearings are typically anchored into abutments with anchor bolts through their baseplate. An expansion bearing will allow for thermal expansion present in the superstructure to take the form of longitudinal translation of the superstructure. The bearing will transfer some horizontal loading from thermal loads and braking/traction forces but the majority of the load will be dissipated through displacement of the expansion bearing, with a small amount transferred to the abutment itself. Fixed bearings will feature a design accounting for the horizontal forces due to braking and traction forces as well as the forces due to thermal loads, but these are mostly mitigated by allowing the superstructure to expand and contract at the expansion bearings.

The bearings on a conventional abutment sit on the bearing seat. Bearing seats feature additional reinforcement to accommodate the loading (ODOT, 2022). The beam seat will transfer the loading from the superstructure to the abutment stem or cap. The cap or stem is designed specifically for vertical loading from the beams (Coletti, 2022). In the case of a tall abutment, the stem will also be designed as a retaining wall with a combination of vertical loading from the superstructure and lateral loading from the soil pressure of the backfill. Depending on the height of the tall abutment, torsional analysis may be warranted (Coletti, 2022).

The backwall of a conventional abutment serves as a retaining wall keeping the backfill from the ends of girders and the bearing seat. In conventional abutment design, backwalls are usually considered to act as cantilevered retaining walls (Coletti, 2022). Depending on the geometry of the abutment and the approach slab, the backwall may see lateral loads from braking and traction forces acting on the approach slab (Coletti, 2022).

Wingwalls act similar to retaining walls, preventing backfill from spilling out the sides of the abutment. Conventional abutment wingwall designs depend on their connection to the abutment. If the wingwalls are rigidly cast with the rest of the abutment, their designs will need to consider the loadings on and from the abutment. Like retaining walls, wingwalls can be founded on spread footings or deep foundations (Coletti, 2022). In some cases, wingwalls attached to the abutment may be cantilevered from the stem (Coletti, 2022). When wingwalls are cast with the abutment, the loading from earth pressure on the wingwalls should be incorporated in the structural analysis of the abutment. If the wingwalls are particularly large or long, they will likely need to be founded on a deep foundation.

Conventional abutments are much more flexible in terms of applicability than integral or semi-integral abutments. Their separation between superstructure and substructure mitigates the issues caused by long spans expanding or contracting. Ohio allows for conventional abutments to be used for almost any skew (ODOT, 2022). Conventional abutments can also be used for steel bridges greater than 400ft and concrete bridges greater than 575ft (ODOT, 2022). This flexibility makes their use common in projects with larger and more complex superstructure requirements. Refer to Figure 4 in the appendix for the chart used by ODOT to determine the applicability of an abutment given geometric parameters.

The characteristic separation of superstructure and substructure does come with some issues. The design necessitates an expansion joint between spans or between the deck and the approach slab. These expansion joints are typically sealed with a seal; however, the insulation wears down over time and typically fails. Joints with deteriorated insulation provide a route for water and roadway salt to infiltrate into the bearings, beam or girder ends and substructure elements such as the abutment or piers. Water and roadway salt accelerate corrosion of bearings and the beam or girder ends and can shorten the lifespan of structural concrete. At the deck level, expansion joints are vulnerable to snowplow blades and heavy trucks. If portions of the joint armor break off, the corners of the deck can become exposed and susceptible to cracking or breaking under heavy loads.

The downsides of expansion joints cause many issues with maintenance over the lifetime of a bridge supported by conventional abutments. Many DOTs, especially in the US have pursued alternative forms of abutment design. There are two alternative types of abutments, integral abutments, and semi-integral abutments. Both seek to eliminate the need for expansion joints and to address the issues caused by them by encasing girders in the backwall. While this does solve the expansion joint problem, there are many other considerations that must be made.

Integral Abutments

A characteristic feature of integral abutments is the encasement of girders in the abutment backwalls. This eliminates the need for bearings or a beam seat. Joints between the approach slab and the bridge deck are also no longer necessary. A jointless condition prevents the common problems found in conventional abutments of water exposure to the bearings or substructure elements. There is also no longer a point where snowplows can catch the joint armor of the deck or approach slab, a problem often seen in conventional abutments in snowy areas. Instead of distinct expansion or fixed conditions, the movement of the abutment accommodates thermal expansion or contraction of superstructure elements. Consequently, the design of the backwall now features more in-depth calculations of longitudinal loading conditions. The thermal loading of the superstructure now pushes the backwall into the soil, increasing the effective stresses it experiences. Design of the backwall of an integral abutment typically considers it as a beam with the encased girders acting as supports and the earth pressures due to the soil acting as a distributed load (Coletti, 2022). This consideration allows for adequate design strength during thermal expansion. Refer to Figure 2 of the Appendix for the ODOT standard drawing of an integral abutment.

If an integral abutment features wingwalls, there are some differences from wingwalls of conventional abutments. Wingwalls tend to be smaller on integral abutments compared to conventional abutments (Coletti, 2022). Additionally, a design decision needs to be made on whether the wingwall is cast with the abutment or independent. Some European countries show preference for wingwalls to be cast with the abutment (White, 2007). In cases such as this, piles should not be used to support the wingwalls. The wingwalls will move with the abutment and pile-founded wingwalls can cause stresses to develop in the abutment and/or wingwalls. It is recommended that in cases of wingwalls on integral abutments, piles not be used as wingwall foundations (Coletti, 2022). Wingwalls may need to feature expansion joints with the abutment. The expansion joints allow for independent movement between the abutment and the wingwalls, while also allowing for expansion.

The design of integral abutment foundations tends to be more complicated than conventional abutments. Since the foundations of integral abutments are designed to rotate and in some cases translate longitudinally, the design must consider allowing movement against soil.

Most US states require pile foundations to be used, usually in a single row (though European countries do not require pile foundations in integral abutments) (White, 2007). The single row of piles utilized allows for rotation of the abutment about the bottom of its footing when the superstructure exerts longitudinal forces during temperature cycles of expansion and contraction. During colder temperatures, as the superstructure shrinks, the abutments rotate inwards, while during warmer temperatures, as the superstructure expands, the abutments rotate outwards.

There are several issues caused by this cyclical rotation inwards and outwards. Because this rotation occurs about the bottom of the foundation, the deflection is greatest at the top of the abutment. When the top displaces inwards, a void is created. This void is filled by the retained soil. When the superstructure expands again, the soil is not compressible enough for the abutment to return to its original position. This can cause the bridge length to “shrink” as the abutments slowly move inward over time (Horvath, 2005). This shrinkage can be exacerbated by concrete shrinkage of the deck and/or abutment (Frosch, 2011). In addition, over time as more and more soil builds up, the earth pressure experienced by the abutment will increase. This effect is typically known as “ratcheting” (Sigdel, 2021). Over time, this ratcheting effect increases earth pressures on the abutment, however long-term research suggests this does not increase indefinitely, with ratcheting effects decreasing in magnitude annually, eventually reaching a steady state of earth pressure (Frosch, 2011). Ratcheting can cause voids to appear under the approach slab, creating a situation where the approach has to effectively “span” an area, something which it likely was not designed to do. This can cause approach slab failure or displacement. If there is no approach slab, these voids can cause a difference in deck and roadway height, leading to a “catch point” for snowplows which can cause damage to deck concrete (Horvath, 2005).

Ratcheting is particularly worrisome in that it can be very difficult to detect before the adverse effects have already taken place. Since it occurs underneath the approach slab and/or roadway, it is almost impossible to find during routine bridge inspections (Horvath, 2005). Ratcheting is primarily an issue addressed through design considerations. There have been a few suggestions for solutions to address the creation of the void caused by inward rotation. Early suggestions featured an inclusion of a highly compressible material as an interface between the abutment and the backfill. The model proposed the material would compress during thermal expansion of the superstructure and then expand back to approximately its original shape during thermal compression of the superstructure (Horvath, 2005). However, in practice this solution was not feasible, since the expansion material would not sufficiently expand to prevent a void from forming and filling with soil (Sigdel, 2021). The compressible material cannot withstand soil pressures and allows for soil to compress it and fill the gap created, effectively allowing ratcheting to occur regardless.

Alternative solutions include the use of a mechanically stabilized earth (MSE) backfill. This backfill would be independent from the abutment. As the abutment moved inward, when ratcheting would otherwise occur, the backfill would strain in tension and maintain its stability (Sigdel, 2021). There would be a gap which would form, but the soil would not sufficiently fill this gap, minimizing the ratcheting effect felt on the abutment during thermal expansion. This void would be filled by a compressible material (Sigdel, 2021). Since the MSE backfill would be holding the soil in tension, the compressible material would not really see much compressive force and would essentially act as a filler material.

There are other critical foundation effects caused by the superstructure movement is an increase in bending stress on piles in the foundation. Piles in an integral abutment are typically specified to be single row (White, 2007), due to the rotational effect of the superstructure movement. Multiple rows of piles would limit the movement of the abutment, increasing its stresses. Additionally, when the abutment rotated about the bottom of its foundation, the row of piles furthest from the point of rotation could experience uplift, an undesirable situation for pile foundations. The single row of piles allows for greater flexibility of the foundation. However, this flexibility comes with important design concerns in the form of fatigue failure. Fatigue failure occurs due to the cyclical nature of superstructure expansion and contraction. During expansion, the piles bend outwards and during contraction, the piles bend inwards. The seasonal and daily cycles of warmer and colder temperatures intensify this bending back and forth and can shorten the lifetime of a pile (Razmi, 2013). Empirical data suggests that the temperature fluctuations during a daily cycle rather than a seasonal cycle are the principal drivers of pile fatigue, likely due to the higher frequency (Razmi, 2013).

The piles used in integral abutment foundations must be flexible, so many times H-piles are used (White, 2007). There remains some discussion of whether the bending of the H piles should occur about its weak or strong axis (Sigdel, 2021). Strong axis bending would stiffen the pile, potentially mitigating bending stress in the pile, but would limit the movement of the abutment and increase the stresses experienced by the concrete. Weak axis bending would essentially do the opposite, allowing for more thermal movement and less stress on the abutment at the cost of more bending stress on and a shorter fatigue life of the piles. In addition to bending stress, the net inward displacement of the abutment creates lateral demand on the piles. A study in Canada suggests the H-piles in integral abutments undergo biaxial bending (Huntley, 2014). Long-term research suggests this lateral demand occurs primarily during the contraction phase of movement, due to a combination of concrete shrinkage and the thermal loads (Frosch, 2011). Thermal expansion likely helps reduce the lateral demand on piles, as it counteracts the lateral loading caused by the inward displacement. Regardless, understanding where the failure of piles occurs can be difficult because the piles are both encased in concrete and below grade. Therefore, it is recommended that the piles be oriented such that their weak axis is parallel to the centerline of the bridge (i.e. bending occurs about the strong axis) to minimize thermal movement, particularly in skewed structures where lateral movement and demand can vary across the length of the abutment (Frosch, 2011).

Great care must be taken when determining the appropriate superstructure for an integral abutment. Because the abutment and superstructure now act together as a frame, the interaction of the superstructure elements with the abutment and soils should be carefully analyzed. Since the girders of an integral abutment bridge are encased in concrete, their expansion is restricted compared to in conventional abutments. This can cause some regions of negative moments to develop within the girders at their interface with the abutment (Coletti, 2022). Negative moments are especially important when considering concrete girders, as additional reinforcement at the top of the section may now be necessary to withstand the higher applied moment. Material selection for the superstructure largely depends on DOT provisions, with states like Ohio allowing structural steel, cast-in-place concrete I-beams, or prestressed concrete box beams (ODOT, 2022). Designers should consider the effects the material of the superstructure could have on the substructure. Empirical evidence suggests material is irrelevant when considering the thermal loads exerted on the abutment (Horvath, 2005), likely because most of the stress experienced by the abutment is due to active and passive earth pressures. However, the displacement due to the thermal effects can be sensitive to the material used. Since concrete shrinks over time, it can increase the inward displacement characteristic of integral abutments (Horvath, 2005).

The geometry of a bridge plays a pivotal role in determining the applicability of integral abutments. Displacement due to thermal loading increases with the length of the bridge, meaning a longer bridge will cause more rotation, translation and stresses on an integral abutment. A larger magnitude of thermal loading can lead to a more robust backwall to accommodate the increased stresses. Models also suggest this can reduce the fatigue life of piles (Razmi, 2013). Much of the geometry requirements of a bridge typically specified by the DOT in which the bridge is being built. In Japan, where seismic considerations are comparatively larger than US or European countries, the maximum allowable length for an integral bridge is 50m (approximately 160ft) (Sigdel, 2021). This is considerably smaller than the US maximum length, which can vary state by state from 500-2000ft (White, 2007). Similarly, countries have variable skew limits. In Europe, England, Finland, and Ireland restrict skew to 30° while Germany and Sweden do not specify a skew limit (White, 2007). Japan does not allow for skewed integral bridges (Sigdel, 2021). US DOT skew limits vary from 15° to 70° (White, 2007). These limitations restrict the design applicability of integral abutments, meaning conventional or semi-integral abutments may be required, regardless of their potential downsides.

Semi-Integral Abutments

Semi-integral abutments, like integral abutments, feature girders encased in a reinforced concrete backwall. Like integral abutments, the backwall moves with the thermal loading from superstructure expansion and contraction. However, unlike integral abutments, semi-integral abutments use expansion bearings to facilitate the movement of the backwall (ODOT, 2022). The bearings are attached to a stem which mostly stays stationary during the abutment's service life. The intent of semi-integral abutments is to eliminate the use of expansion joints (a common infiltration point for corrosion) while mitigating the potential negative effects on the foundations (e.g. ratcheting, pile fatigue failure) of integral abutments. Oftentimes, a pressure relief joint is placed at the far end of the approach slabs for semi-integral and integral abutments, due to the attachment between approach slab and backwall. In some cases, this relief joint may have to be an actual expansion joint, but if this occurs, it is away from structural elements. Refer to Figure 3 of the Appendix for the ODOT standard drawing for a semi-integral abutment. Some variants of semi-integral abutments also include a hinge detail with longitudinal movement taking place within a shear key (Coletti, 2022).

Semi-integral abutments are especially attractive to DOTs (particularly ODOT) because conventional abutments can be converted into semi-integral abutments during bridge rehabilitations. In areas where there is a lot of precipitation and the potential for salt exposure on bearings, this can be an attractive proposition. There is also flexibility in the retaining structures used in semi-integral abutments. Semi-integral abutments are more flexible in the material used to construct them (Horvath, 2005). For bridges where horizontal clearance between the underneath is a concern, MSE walls can be used in front of a stub semi-integral abutment. Ohio forbids the use of MSE walls with integral abutments (ODOT, 2022), likely due to the issues cause by rotations of the abutment.

Since semi-integral abutments are functionally a hybrid between conventional and integral abutments, the design considerations can be similar. For instance, the foundations of semi-integral abutments and conventional abutments are both designed with the intention to stay in the same place. Semi-integral foundations on piles use more than one row of piles (ODOT, 2022), matching conventional abutment details. Semi-integral abutments also use bearings in their designs, so the design process for bearings must take place as it would for a conventional abutment. The additional piles and the lack of intense lateral loading on them extends the lifetime of each individual pile.

There are some similarities in design concerns between integral and semi-integral abutments. Because the backwall expands against soil (typically with a compressible material such as polystyrene between the two), there is soil-structure interactions to consider. The backwall concrete between girders can be viewed similar to a diaphragm. When the superstructure expands and pushes the backwall into the soil, this pressure on the diaphragms can cause problems to develop among many structural elements, including the wingwalls (ODOT, 2022). For this reason, Ohio insists the wingwalls of semi-integral abutments be separate from the superstructure with expansion joint filler (ODOT, 2022). In skewed structures, evidence suggests thermal expansion translates along the diagonal (or centerline of bearings), imparting forces along the length of abutment and onto wingwalls (Hoppe, 2008). Joints help mitigate the issues of these forces acting on the wingwalls.

Superstructure considerations for semi-integral abutments are generally similar to those of integral abutments. Ohio specifies the use of structural steel, prestressed concrete I-beams or box beams (ODOT, 2022). Semi-integral abutments generally are more flexible regarding skew requirements than integral abutments, similar to conventional abutments. Since the bearings are facilitating free expansion, the issues of different longitudinal forces acting on the abutment are minimal when compared to integral abutments. Ohio does not limit skew, however there is a specification to use only straight girders on semi-integral bridges (ODOT, 2022). The combination of the benefits of joint elimination and stability of foundation make semi-integral abutments a strong competitor for abutment types.

Conclusion

The proper selection of an abutment type involves extensive engineering analysis. Bridge engineers must understand how the geotechnical, structural, and roadway elements relate to the analysis of the potential abutment types. The geometry of the bridge can limit the applicability of an abutment type and proper consideration towards DOT requirements is necessary for a truly successful abutment design. While conventional abutments provide flexibility in skew and length requirements, there are several concerns regarding longevity and maintenance costs. Integral abutments, while addressing the concerns caused by expansion joints, have their own issues to be considered. The increased stresses on piles and the rotational movement of the abutments can cause problems with longevity of the substructure. Semi-integral abutments seek to remedy these by allowing movement of the backwall on expansion bearings. Although this addresses the primary issue of integral abutments, semi-integral abutments can still be limited in their application.

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Appendix

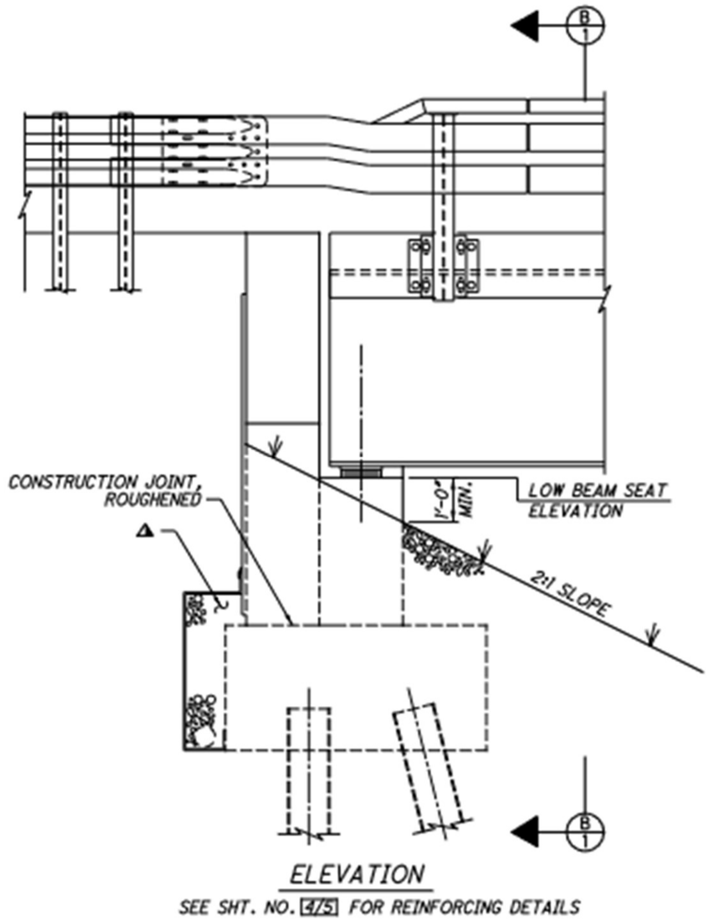

Figure 1 Conventional Abutment (stub shown) ODOT Standard Drawing (ODOT 2022)

Note bearing device and clear joint between superstructure and substructure.

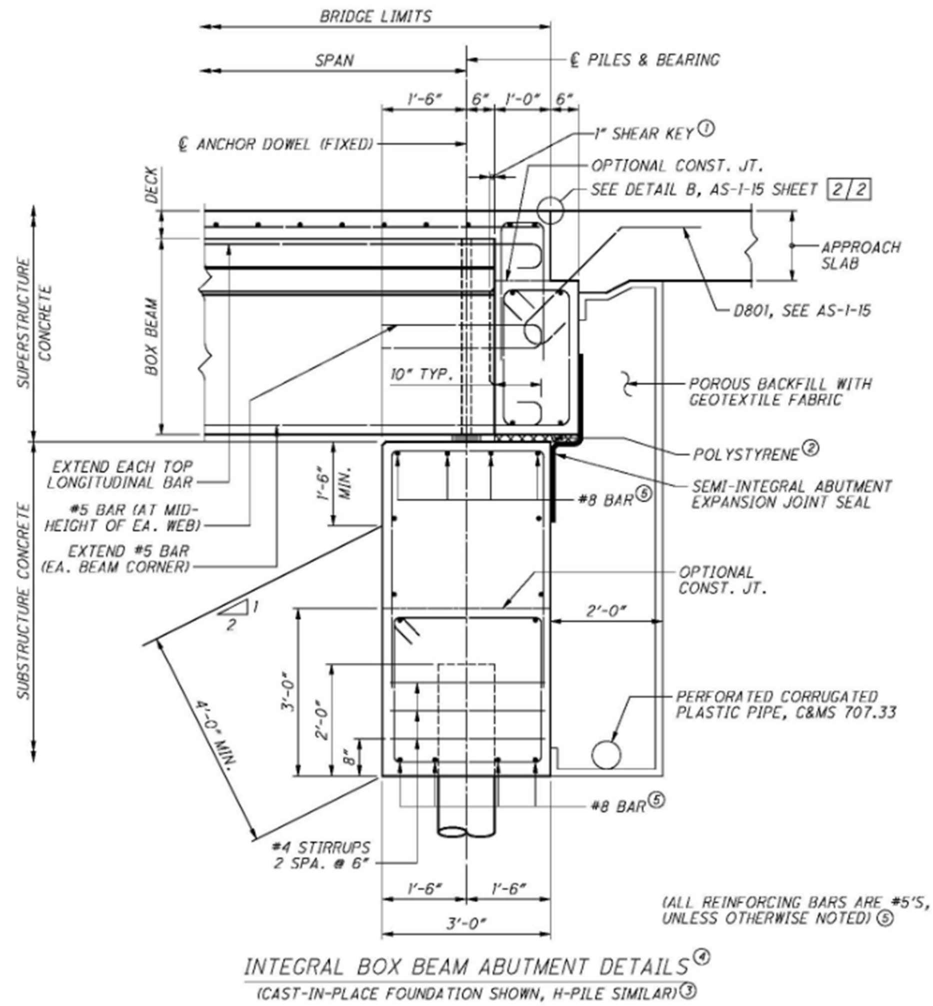

Figure 2 Integral Abutment ODOT Standard Drawing (ODOT 2022)

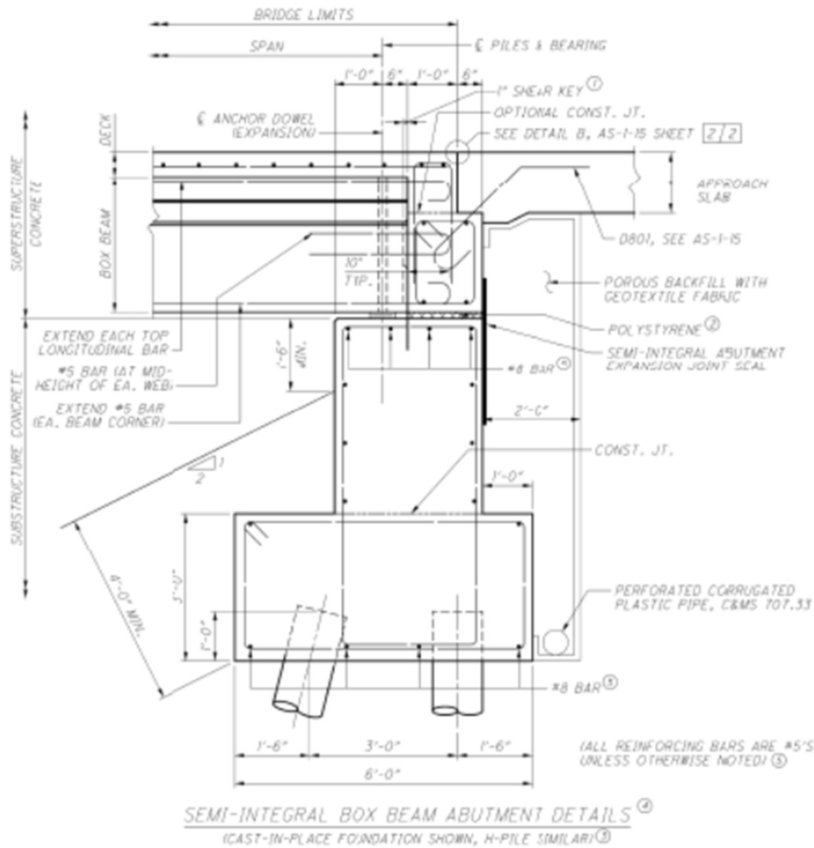

Figure 3 Semi-Integral ODOT Standard Drawing (ODOT 2022)

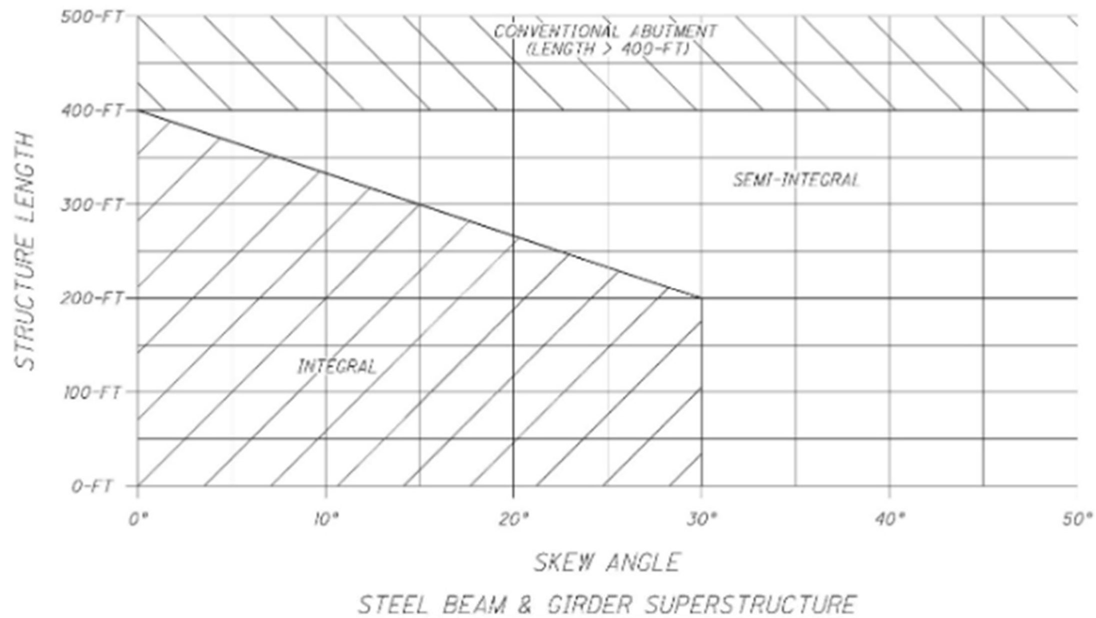

Figure 306-5

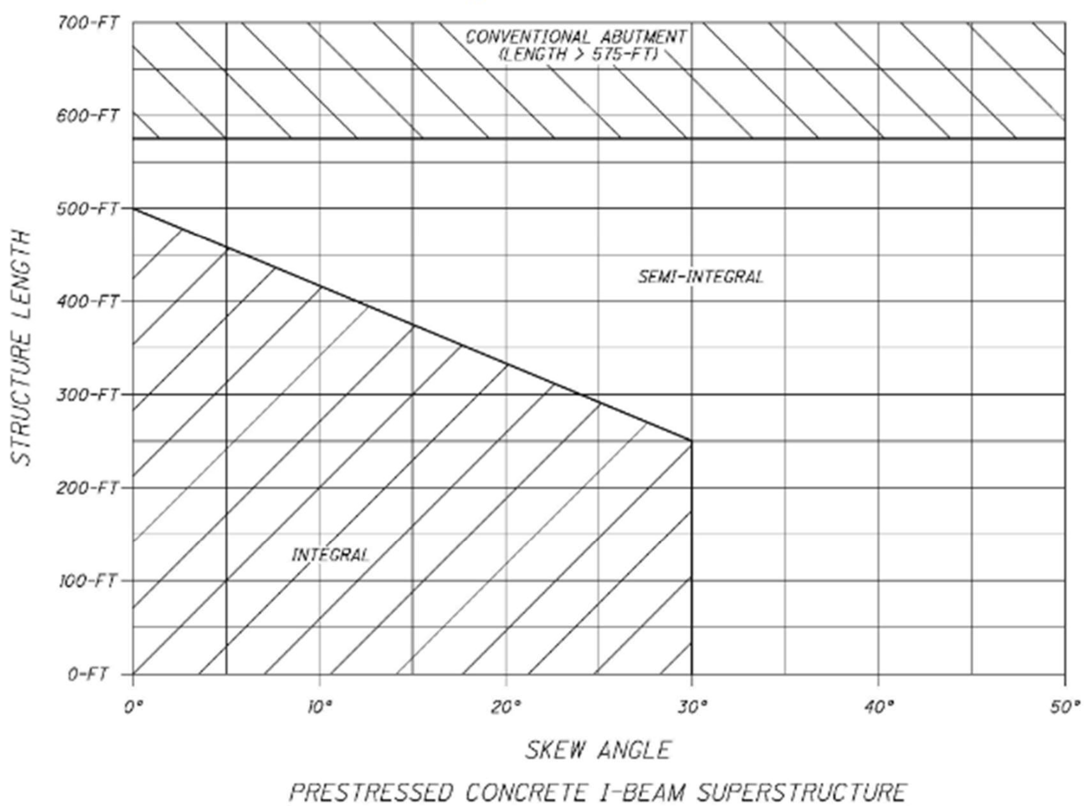

Figure 306-6

Figure 4 Design Chart for Geometric Limitations Given an Abutment Type (ODOT 2022)