Integral Bridges: Attributes and Limitations

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In some areas of the United States, integral bridges are now being used whenever application limits do not favor another type of structure. Integral bridges have numerous favorable attributes and few limitations. Because design provisions can be made for some of the limitations, only application limitations such as length, skew, and curvature should negate the use of integral bridges in favor of their jointed bridge counterparts. Design procedures and details used for the construction of single- and multiple-span integral bridges of continuous moderate length [91 m (300 ft)] are described, and the comparative attributes and limitations of integral and jointed bridges are elaborated on. The integral bridges discussed have shallow, stub-type abutments supported by embankments and piles. For integral bridges with multiple spans, piers are either flexible and attached to the superstructure or semirigid and self-supporting with movable bearings.

Integral structures, or structures without movable joints, are ages old. The most celebrated are the natural arches carved from bedrock by water and wind. The largest such structure is Rainbow Bridge National Monument in Utah near the Arizona border. It is composed of pink sandstone and has a span of 85 m (278 ft).

However, in considering integral bridges built by human beings, one cannot go much further back into recorded history than the first arch bridges containing unreinforced concrete constructed by the Romans. More recently, most are familiar with the construction of reinforced concrete arch bridges in the early decades of this century.

BACKGROUND AND OVERVIEW

Reinforced concrete began as a substitute for stone masonry in the construction of filled spandrel arch bridges. In these bridges, the pavement and spandrel fill are supported on one or more continuously reinforced arched slabs. Although many of the multiple-span spandrel-filled arches were constructed with movable joints in spandrel walls and railings, many of the one- or two-span bridges of this type can be classified as true integral bridges because they were constructed without movable joints. (In this paper, the designation "movable joint" replaces the misnomer "expansion joint.")

By the third and fourth decades of this century, arch bridge construction culminated in the construction of long-span closed- and open-spandrel arch bridges. Although the major supporting elements of these bridges (abutments, piers, and arch ribs) have no movable joints, they are not true integral bridges because the deck slabs and spandrel walls have movable joints at each intermediate pier and occasionally in the deck slabs and spandrel walls within each span.

By midcentury, however, many transportation departments were building concrete rigid frame bridges. These bridges represented a standard type of construction for many transportation departments. Those built in Canada by the province of Ontario are good examples. Although vertical movable joints are used between the bridges and their lateral wingwalls, the bridges can be classified as integral because they have no movable joints in their decks or primary supporting elements.

The construction of rigid frame bridges was paralleled by the construction of bridges with multiple-span, continuous-slab beams or girders. Ultimately, the overall economy of continuous construction made practicable the use of multiple spans, embankments, and small stub-type abutments supported on a single row of flexible piles in lieu of a conventional single- or multiple-span bridge with wall-type abutments (Figure 1). Many of the shortest of these bridges—those shorter than 61 m (200 ft)—were constructed without movable deck joints. The economy, durability, and simplicity of these early integral designs led to the use of this type of construction for progressively longer spans.

Thus, although various types of integral bridges have been constructed for centuries, the term "integral bridge" is now generally used to refer to continuous jointless bridges with single and multiple spans and capped-pile stub-type abutments (Figure 2).

Piers for integral bridges can be of any type. If the inherent flexibility of a chosen type will accommodate structure movements, the piers may be built integrally with the superstructure or connected to it with anchor bolts. Otherwise, piers are designed as semirigid self-supporting substructures with movable bearings between them and the superstructure.

ATTRIBUTES AND LIMITATIONS

The popularity of integral bridges has grown with their number (*1–3*). It soon became evident that these bridges, which were originally built as a reaction to the destructive effects of leaking deck joints and massive pavement pressures, had many more attributes and fewer limitations than their jointed counterparts. Interestingly enough, these attributes not only reduced a bridge's first cost and life-cycle cost, they also reduced the cost of its own future modification (e.g., widening) and its eventual replacement. Integral bridges have been found to be an ideal structure for secondary road systems for states and counties, and with thoughtful crafting they are becoming popular for rural and urban primary and Interstate systems.

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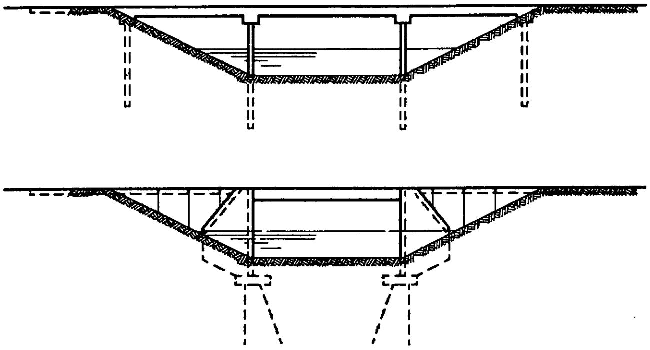

FIGURE 1 Different bridge types for the same site: *(top)* multiple-span integral bridge with stub-type abutments; *(bottom)* single span with movable bearings and wall-type abutments.

Although their jointless construction and resistance to pavement pressure and consequent long-term durability appear to be the primary attributes that first motivated the construction of longer and longer integral bridges, it also appears that their simple design, rapid construction, and other attributes have gained favor for them as these attributes become more widely recognized.

For design engineers and engineer administrators who are considering integral bridges for the first time, a review of the discussion in this paper should help to explain why these bridges are now being constructed with increasing frequency.

Attributes

Because discussions of attributes (and limitations) of integral bridges would have little significance unless they were considered with respect to another bridge type with familiar characteristics, the descriptions that follow and the comparisons that are made all refer to similar single-span or multiple-span continuous deck-type structures with movable deck joints at abutments and with both fixed and movable bearings.

Simple Design

Where abutments and piers of a continuous bridge are each supported by a single row of piles attached to the superstructure or where self-supporting piers are separated from the superstructure by movable bearings, an integral bridge may, for analysis and design purposes, be considered a continuous frame with a single horizontal member and two or more vertical members. When the stiffness and distribution factors are calculated for such a frame, the vertical members are so flexible when compared with the horizontal member that the horizontal member may be assumed to have simple supports. Consequently, except for the design of the continuity connections at abutments, frame action in integral bridges can be neglected in considering the effects of vertical loads applied to superstructures.

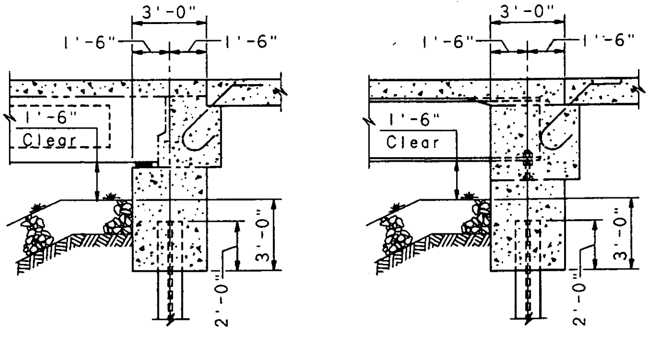

FIGURE 2 Capped-pile stub-type abutments for integral bridges: *(left)* for prestressed concrete box-beam stringers; *(right)* for steel I-beam stringers.

The design of integral bridges is further simplified because piers and abutments generally need not be designed to resist either lateral or longitudinal loads. This is possible because the laterally and longitudinally rigid concrete deck slab is rigidly attached to both abutments, and the abutments are rigidly restrained by the confining embankments. Consequently, essentially all lateral and longitudinal loads applied to the superstructures of integral bridges are distributed directly to abutment embankments. As a result, piers and abutments need not be designed to resist horizontal loads applied to superstructures.

The design of abutment-superstructure continuity connections and transverse wingwalls can be standardized for a wide range of bridge applications. A nominal amount of reinforcement will be suitable to resist the slight live and dead loads typical of such applications plus a wide range of secondary effects (shrinkage, creep, passive pressure, etc.). Also, a nominal amount of reinforcement can be provided for transverse wingwalls to resist the maximum anticipated passive pressure. Once these standard details are established, each bridge abutment can be configured and reinforced for the vertical reactions associated with various roadway widths and span lengths. In general, this consists of no more than the determination of an appropriate pile load and spacing and pile cap reinforcement.

The design of piers is similarly accomplished. Essentially all horizontal superstructure loads are distributed to approach embankments, and moments resulting from pier-superstructure continuity are negligible. Therefore, piers of integral bridges (capped-pile or free-standing types with movable bearings) need be designed only for vertical superstructure and pier loads and for lateral loads that may be applied directly to the piers (streamflow, stream debris, earth pressure, wind). Where these lateral pier loads are small, and this is usually the case, most piers, like abutments, can be designed essentially for vertical loads alone.

For flexible piers that receive much of their lateral support from their connection to the superstructure, construction procedures are necessary to ensure that these piers are not laterally loaded until after they have been connected to the superstructure and the continuity connections to the superstructure abutment have been completed.

Because the superstructure and abutment embankments resist primary lateral loads, piers (piles, columns, footings, foundations) of integral bridges may be reduced to minimum sizes and dimensions. Battered piles are not required. Fixed piers are not required. In general, pier design can be simplified to the extent that standard designs can be developed for a wide range of roadway widths and span lengths.

Jointless Construction

The primary attribute of integral bridges is their jointless construction. To fully appreciate this attribute, one must be familiar with the performance of bridges with movable joints.

Open-deck joints permit contaminated deck drainage to penetrate joints and cause extensive below-deck deterioration. Closed joints and sealed joints give a measure of protection from deck drainage deterioration. However, all movable deck joints (open, closed, or sealed) are vulnerable to the destructive effects of approach pavement growth and pressure. Bridges with movable deck joints constructed in conjunction with rigid, jointed approach pavement have inadvertently functioned as elaborate and expensive pavement pressure relief joints. As approach pavements grow and the moving deck joints accommodate this growth, bridges are progressively squeezed until the movable joints are closed. Thereafter, additional pavement growth and bridge elongation generate sufficient pavement pressure to crush joint seals and to fracture abutment backwalls and bridge seats. Consequently, the avoidance of such joints obviates the need for maintenance-prone joint seals and the extensive pressure-damage repair that has come to be associated with them.

As a secondary benefit, smooth jointless construction improves vehicular riding quality and diminishes vehicular impact stress levels.

Pressure Resistance

The solid, jointless construction of integral bridges distributes longitudinal pavement pressures over a total superstructure area substantially greater than that of the approach pavement cross section. Consequently, approach pavements are more likely to fail by progressive localized fracturing or instantaneous buckling than the more pressure-resistant bridge superstructure. Unless approaches to integral bridges are furnished with cycle control joints that are appropriately designed—joints that facilitate the thermal cycling of the bridge and attached approach slabs—they are more likely to experience early distress because restrained expansion of the bridge contributes to the generation of pavement pressure.

Because integral bridges are capable of sustaining significant longitudinal compression without distress, almost any pressure relief joint used by maintenance forces to relieve pavement pressure would be suitable for them. However, jointed bridges need highly efficient pressure relief joints if pavement pressures are to be reduced low enough to keep deck joints functioning. Few such pressure relief joints are being used by pavement design or maintenance engineers.

Rapid Construction

Numerous features of integral bridges facilitate their rapid construction, and these features are probably responsible for much of the outstanding economy that has been achieved by their construction. Dry construction, simple members, broad tolerances, few construction joints, few parts, few materials, elimination of labor-intensive practices, and many other features combine to make possible completion of such structures in a single, short construction season. The more rapid construction is possible even when the structures have to be built in stages to maintain traffic. Consider the following features in more detail.

Embankments Embankments can be placed and constructed with large earth-moving and compaction equipment. Only limited use of hand-operated compaction equipment is needed.

Cofferdams Integral bridges, especially those constructed with capped-pile or drilled-shaft piers, can be constructed with fewer delays due to inclement weather and stream flooding. Abutment excavations and pile driving near the top of approach embankments can be done without cofferdams and generally without the need for dewatering. Foundation construction can progress as fast as pier and abutment piling can be driven. Subsequently, pile cap and superstructure construction can proceed with little regard for streamwater levels.

Small Excavations At abutment benches, excavations need be no more than 0.6 to 0.9 m (2 to 3 ft) deep.

Vertical Piles At abutments, vertical piles are uniformly spaced and driven in a single horizontal row. In contrast, the typical abutment foundation of jointed bridges consists of two or more rows of both vertical and battered piles.

Pier piles also are uniformly spaced and driven vertically in a single horizontal row. This arrangement avoids the need for pile clusters with some battered piles for each column footing, the typical pier foundation for many cap and column piers of jointed bridges. For bridge sites with high water levels, driving piles for pier footings is more difficult because the piles must be driven inside deep cofferdams.

Simple Forms Pier and abutment pile caps are formed quickly because they are usually composed of simple rectangular shapes.

Few Joints Few construction joints are used for integral bridges. Consequently, few concrete placement and curing days are needed. For example, no more than four concrete placement days are needed for most integral bridges. Only one day each is required for placing pile caps, continuity connections, deck slab, and approach slabs. Single-span integral bridges in some states have been simplified to the extent that only two days are required; the second day is necessary only to place separately cast approach slabs. In contrast, constructing most jointed bridges requires five or more placement days and subsequent curing days.

Few Parts Fixed and movable bearings, armor for deck joints, and deck joint seals are unnecessary. The normal delays associated with deck joint installation, adjustment, and anchorage are avoided.

Broad Tolerances The close construction tolerances usually associated with jointed bridges are not necessary for integral bridges. For example, the elevation, slope, and uniformity of bridge seats are not important because only rough-surfaced construction joints are required.

Reduced Removals Using typical multiple-span integral bridges with embankments and stub abutments to replace shorter bridges with wall-type abutments permits new bridges to be constructed without requiring the complete removal of existing substructures. The new bridges can be configured to straddle existing foundations (Figure 3), and where existing abutments are located in the new embankments, most of the existing abutments need not be removed. At many sites, significant savings are possible. For example, where normal water levels are high, complete removal of existing substructures could require the building of large cofferdams for this purpose alone.

Simple Beam Seats Some of the labor-intensive practices required for jointed bridge construction are either eliminated or substantially simplified in integral bridge construction. For example, consider the problem of providing appropriate loading surfaces for the elastomeric bearings of side-by-side and spread prestressed box-beam bridges.

Side-by-side prestressed box beams must be canted laterally to match the deck crown and tilted longitudinally to accommodate bridge grade. Also, because the ends of these beams are sloped owing to residual camber, adjustments usually need to be made in beam bottoms, bearings, or bridge seats to compensate for these geometric irregularities and provide parallel loading surfaces for elastomeric bearings. A number of options are available to the designer:

1. A longitudinally tapered recess can be cast in beam bottoms to match a longitudinally level and laterally crowned bridge seat surface,
2. Bridge seats can be sloped to match the orientation of beam bottoms, and
3. A tapered metal laminate can be molded within the bearings to compensate for differences in the longitudinal orientation of beam bottoms and seat surfaces, and bridge seats can be laterally crowned to match the canted beams.

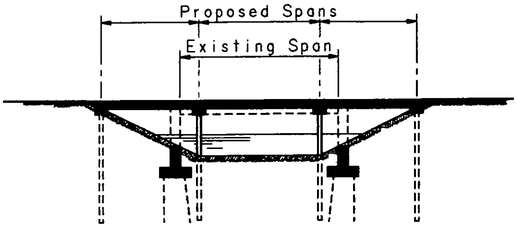

FIGURE 3 New bridge straddles old foundations.

If this is not complex enough, the specific provisions adopted to compensate for crown, grade, and camber may, in some bridges, have to be unique for each bridge seat because bearing geometry changes from one substructure to the next as a result of changes in grade and span lengths. In addition, poor estimates of residual camber, differences in residual camber from beam to beam, skew effects, errors in computing actual surface orientations, and errors in construction make the attainment of parallel loading surfaces uncertain. Consequently, even after all these considerations have been accounted for, occasionally it is necessary to use shims under elastomeric bearings to obtain solid seating of beams on bridge seats.

Integral bridge construction makes most of these considerations and procedures unnecessary. Because beams of integral bridges need only temporary support until continuity connections have been cast, a narrow temporary elastomeric erection strip can be used on a temporary bridge seat surface to support the beams. After continuity connections are cast and cured, all the beam reactions (dead, live, and impact loads) will be uniformly supported by cast-in-place continuity connections, connections that are far superior in supporting superstructure loads to the series of separate and uncertainly loaded elastomeric bearings characteristic of jointed box-beam bridges.

Because concrete or steel I-beams are placed vertically, crown effects need not be considered when appropriate bearings and bridge seats are provided. However, even for I-beam bridges, the use of integral construction (continuity connections) considerably simplifies bridge seat and bearing requirements and improves the distribution of superstructure reactions.

Elimination of Bearing Anchor Bars For the typical jointed bridge, superstructures are usually fixed at one or more substructure elements, usually at an intermediate pier. For side-by-side prestressed box-beam bridges, this fixing often is done by placing anchor bars down through precast holes in the box beams and into field-drilled holes in bridge seats. Because of the uncertainties of beam fit-up, beam length, and substructure locations, holes in the bridge seat must be field drilled after all beams have been placed and compacted together. Considering the errors that are likely to occur in locating substructures accurately and the bridge-seat reinforcement in these substructures, it is reasonable to assume that some primary bridge-seat reinforcement is cut by field drilling anchor bar holes.

Because superstructures of integral bridges receive lateral and longitudinal support from abutment embankments, only flexible piers not integrally constructed with superstructures (the types of piers that depend upon the superstructure for lateral and longitudinal support) need to be provided with anchor bars and field-drilled holes. All other pier types (flexible integral piers and self-supporting piers with movable bearings) do not need bearing anchor dowels or field-drilled anchor dowel holes. For both pier types, because field-drilled anchors are not needed, the potential damage associated with drilling anchor-bar holes in the field is avoided.

Of particular significance is the saving per hour of work made possible by eliminating the labor-intensive procedures of drilling and cleaning the holes and placing anchor bars and grout. This labor can be significant when such anchors are located in each beam and at every support.

Eliminating holes for field-drilled anchor bars is particularly important in projects for bridge modification. For example, in replacing the superstructure of an existing bridge (and this type of bridge modification occurs increasingly frequently), conversion of a jointed bridge to an integral bridge with continuity connections cast in place at abutments enables the designer, when working with self-supporting piers, to eliminate attachments between piers and superstructure. Fixed bearings and their anchor bars can be eliminated. Consequently, the designer of such a project can, by eliminating the need to field-drill anchor holes, avoid the probability of cutting existing primary pier cap reinforcement.

Broad-Span Ratios

The ratio of end span to center span of continuous spans (L_e/L_c) is generally set at or near 0.8 to achieve stable superstructures and a balanced beam design. This is the ratio most often used for stream crossings. Lesser ratios are often used for grade separation structures where short end spans are needed to achieve the shortest possible bridge length. However, for sites where a ratio of less than 0.6 is necessary for jointed bridges, provisions must be made to prevent beam uplift during deck placement and superstructure uplift because of movement of vehicular traffic. Such provisions can become complex and expensive when bearings must be provided that will allow horizontal movement of the superstructure but prevent uplift.

Integral bridges, on the other hand, are more resistant to uplift because the abutment weight resists it. Thus, a span ratio of 0.5 can be used without any change in the integral bridge design. For the smallest span ratios, a procedure for deck slab placement can be used to counteract uplift during construction.

Earthquake Resistance

Because decks of integral bridges are rigidly connected to both abutments and consequently to both embankments, these bridges are in fact part of the ground and will move with the ground during earthquakes. Consequently, when integral bridges are constructed on stable embankments and subsoils, they should have an adequate response to most earthquakes.

For an integral bridge located across a fault line—a highly unlikely situation—differential lateral movement of the ground at the fault line could seriously stress the bridge deck, but the integral construction of the structure should enable it to resist.

Simplified Widening and Replacement

Many of the bridges placed on the highway system in the past were designed for immediate needs with little consideration for future requirements. Through arches of concrete, through trusses of steel, and bridges with wall-type abutments with flared wingwalls are prime examples of such bridges. Most often, through structures have to be completely replaced when increased traffic and traffic speeds necessitate building wider roadways. Widening bridges with wall-type abutments and flared wingwalls is complex and expensive.

In contrast, integral bridges with straight capped-pile substructures are convenient to widen and easy to replace if future demands have not been accurately foreseen. Of particular significance is the fact that their substructures (the piling) can be recapped and reused or, if necessary, they can be withdrawn or left in place. They avoid the necessity of building extensive foundations that interfere with the placement of future foundations.

Many of the stream crossings in Ohio—and presumably the same is true for many states and provinces—have been spanned by at least three separate earlier bridges, with a fourth presently being planned. For many of these early bridges, the foundations have been left in place. Consequently, when planning today's replacement structure for small stream crossings, the engineer finds that parts of the streambed are filled with the old foundations. With the use of capped-pile substructures, the new substructure can be placed to clear existing foundations and avoid the expense of removing them. Also, the greater span ratio range gives the integral bridge great adaptability for the foundation-filled bridge sites.

Improvement in Live Load Distribution

Superstructures that are integrally constructed with capped-pile abutments and piers instead of separated from them by numbers of compressible elastomeric bearings give vehicular wheel loads broader distribution than would otherwise be possible. This arrangement reduces superstructure service load stresses.

Limitations

High Abutment-Pile Stresses

Except for abutment piling and wingwalls, the various members of integral bridges are subjected to essentially the same levels of primary stresses (dead load, live load, impact, etc.) and secondary stresses (shrinkage, creep, thermal gradients, etc.) as their jointed bridge counterparts. However, because the bending resistance of the vertical piling of integral bridge abutments will resist the lengthening and shortening of bridge superstructures responding to temperature changes, the piling of long integral bridges can be subjected to flexural stresses considerably greater than those of their jointed bridge counterparts. For longer integral bridges, research with abutments supported by steel piles has shown that abutment piling stresses of integral bridges can approach, equal, or even exceed the yield strength of pile material.

Such flexural piling stresses, if they are large enough, will result in the formation of plastic hinges that will limit the flexural resistance of the piles to additional superstructure elongation. At the same time, the laterally supported piles should retain their capacity to sustain vertical loads.

Because piles of integral bridges may be subjected to high bending stresses, only suitable pile types should be used for these applications. Such piles should retain sufficient axial load capacity while localized pile transformations occur that will reduce the resistance to bending. For this reason, only steel H-piles or appropriately reinforced concrete or prestressed concrete piles should be used to support abutments of the longer [>91 m (>300 ft)] integral bridges.

For shorter integral bridges, pile flexural stresses should be well within normal allowable stress levels for the material under consideration.

In addition to the most appropriate piling, other provisions can be considered to reduce the resistance of piles to lateral abutment movement: Steel H-piles can be oriented to place the weak axis parallel to the abutment centerline, bridge skews can be limited (typically <30 degrees), piles can be placed in prebored holes filled with fine granular material, pile-footing connections can be altered to reduce the resistance of the piles to bending at this junction, appropriate reinforcement can be placed in concrete piles to facilitate the formation of hinges, and so forth.

For short- and medium-length bridges provided with the usual single row of cast-in-place concrete, precast concrete, or steel H-piles, pile flexural stresses should be well within the elastic range. No unusual provisions should need to be made in their design.

Limited Applications

The superior economy of integral bridges is due to their ability, within a limited application range, to satisfy all functional requirements with safety, durability, and optimal economy. They are not broadly adaptable to most bridge applications as are their jointed bridge counterparts.

Integral bridges with abutments supported on single rows of piling should be limited in a number of ways based on the primary design features that have been incorporated into standard designs. In general, their length should be limited for two reasons: to minimize passive pressure effects and to limit bridge movements to those that can be accommodated by the movement range of approach slab–approach pavement cycle control joints and standard approach guardrail connections. They should not be used where curved beams or beams with horizontal bends are used. They should not be used for extreme skews (>30 degrees). They should not be used where abutment piles cannot be driven through at least 3 to 4.5 m (10 to 15 ft) of overburden. They should not be used at sites where the stability of subsoils is uncertain or where vertical abutment settlement may be significant (where it cannot be effectively compensated for by added roadway overlays alone). Finally, they should not be used at sites where they can become submerged unless the superstructure is vented, vertically restrained to resist uplift due to superstructure buoyancy, or both.

Buoyancy

Because of their jointless construction, many types of integral bridges are subject to uplift when they become submerged. This is true for many I-beam bridges and some spread box-beam bridges.

The weight of diaphragms and abutments provides some resistance to uplift, but generally some positive design provisions must be made to ensure that integral bridges have a reasonable factor of safety against flotation. I-beam webs can be pierced near top flanges by 76.2-mm (3-in.) diameter holes spaced uniformly throughout the beam length; the space between spread boxes can also be vented by placing 76.2-mm (3-in.) minimum diameter horizontal vent ducts near the top flange of all beams. These ducts should pass completely through the beams from one web to the other, and they should be placed in concrete diaphragms or be completely encased in concrete to prevent floodwaters from entering beam voids. Counterweights could be used, but their weight must be taken into account during beam design. Uplift restraints could be provided at pier bearings, or some piers can be integrally constructed with the superstructure to add sufficient uplift restraint to counteract buoyancy.

In lieu of vent holes, added weight, uplift restraints, or integral pier construction, most buoyant structures should be used only at those bridge sites where the highest floodwater levels are well below the superstructure.

Construction Procedures

Embankments Abutments and piers of integral bridges composed primarily of a single row of piles have a very limited resistance to lateral loads. So they must be constructed in a way that either controls or eliminates lateral earth movements. In this respect, most major earthwork must be placed and compacted before piling is driven to ensure that lateral movement of subsoils both below and within embankments has been allowed to stabilize before piles are driven. A typical plan note used for this purpose can be phrased as follows:

> EMBANKMENTS shall be constructed up to the subgrade for a distance of 61 m (200 ft) (other) back of abutments before excavation is made for abutments, prebored holes placed, and pier and abutment piles driven.

The limitation given above for piers is important. Even though piers may be located beyond the toe of abutment embankments, they can be adversely affected by subsurface movement if they are placed before embankment construction has been completed. However, if they must be placed before embankment construction, they also must be of the type that can resist lateral earth pressure without depending upon their attachment to the superstructure for support.

Abutment and Approach Slab Concrete Because concrete continuity connections at abutments and approach slabs must be cast integrally with superstructures and superstructures are continuously responding to changing ambient temperatures, such placement, especially for long bridges, should be controlled to minimize the effect of superstructure movement on fresh concrete.

It is generally not feasible to restrict concrete placement to those days of the year with the smallest temperature range and consequently to periods of the smallest potential for large superstructure movements. But it is practicable to limit concrete placement during daily periods when the superstructure movement is the smallest, generally shortly after the ambient temperature approaches, reaches, and departs from the day's peak temperature. A plan note to provide such control and some protection for freshly placed concrete can be phrased somewhat as follows:

> CONCRETE for continuity connections at abutments shall be placed and completed at least four hours prior to the concrete placement day's peak ambient temperature.

Approach slab connections to abutments should be similarly protected from the effects of the superstructure's response to ambient temperature changes. A plan note somewhat as follows can be used:

> APPROACH SLAB concrete shall be placed towards the superstructure and be completed at least four hours prior to the concrete placement day's peak ambient temperature.

To avoid damaging freshly placed concrete continuity connections during sudden ambient temperature changes, especially for long superstructures, in some states superstructure beams are mechanically fastened to abutment pile caps before continuity connections are placed. Thus, after this attachment is completed, the continuity connection (abutment backwall) can be placed without concern for changes in the ambient temperature because concrete is being placed on a pile cap, a cap that is moving with the superstructure. However, even for these structures, control of approach slab concrete is still necessary.

Deck Slab Concrete Deck slab placement on integral bridges with short end spans must be controlled to eliminate uplift of beams during concrete placement. This can occur when both deck slabs and continuity connections at abutments (integral backwalls) are placed simultaneously. To avoid uplift in these applications, continuity connections should be placed first and cured adequately before placement of deck slab concrete.

Approach Slabs

Full-width approach slabs should be provided for most integral bridges. They should be tied to the bridge to avoid having the slabs shoved off their seats by the constant horizontal cycling of the bridge as it responds to daily temperature changes. To facilitate the slab's movement, a sealed cycle-control joint should be provided between approach slabs and approach pavements to accommodate the cycling of the approach slabs. The sealed joint should also prevent roadway drainage from penetrating the joints and flooding the subbase. To protect the joints, approach slabs, and bridge from pavement pressure, an effective pavement pressure relief joint also should be provided in all jointed approach pavement.

Approach slabs have a number of beneficial effects. By spanning between abutments and approach embankment, approach slabs prevent vehicular traffic from consolidating the backfill adjacent to the abutment, thereby diminishing passive pressure effects. If the approach slabs are long enough, they eliminate live-load surcharge on abutment backfill. They help to control roadway drainage by conducting it across the abutment backfill to the bridge or pavement approaches and prevent erosion of abutment backfill or saturation and freezing of the backfill. Finally, they serve as a ramp from the rigidly supported abutments to approach pavements supported on consolidating embankments, and thereby help to retain a serviceable riding surface and minimize vehicular impact.

However, approach slabs tied to integral bridges become part of the bridges and respond to temperature and moisture changes. Consequently, they effectively increase the overall structure length and require cycle-control joints with greater movement ranges.

To minimize the amount of force necessary to move the slabs, they should be cast on smooth, low-friction (polyethylene, filter-fabric, etc.) surfaces.

Cycle-Control Joints

Integral bridges with attached approach slabs lengthen and shorten in respone to temperature and moisture changes. For such structures built adjacent to rigid approach pavement, the boundary between the approach slabs and approach pavement should be provided with cycle-control joints to facilitate such movement. Otherwise, the cycling of both structure and approach slabs can generate pressures sufficient to fracture the approach pavement either progressively or instantaneously (blow-up).

Over time, jointed approach pavement will lengthen progressively (grow). Where such progressive movement is restrained by an integral bridge, substantial longitudinal pressures will be generated in the pavements and adjacent bridge. To control such pressures, pressure relief joints should be used between rigid approach pavement and integral bridges.

Consequently, two types of joints are required adjacent to integral bridges. One should facilitate the cycling of the bridge and attached approach slabs, and the other should be capable of responding to the progressive growth of the approach pavement. Designs by four transportation departments are given elsewhere (*4*). All the designs in use have their limitations. To avoid the maintenance problems associated with complex or unusual cycle-control joints, maintenance engineers of the Ohio Department of Transportation (ODOT) prefer simple 0.3-m (12-in.) wide pressure-relief joints for longer integral bridges to facilitate both types of movement. The narrow joints will be progressively compressed by the growing approach pavement. When the bridge and attached approach slabs withdraw during periods of cold temperature, the joints will be open to water and debris. This is the primary fault of this design, but the fault is considered acceptable until a more suitable design becomes available. The joints can be filled by maintenance personnel during cold weather or they will be closed in warm weather by expanding pavement. Ultimately, the joints, approach pavement, and bridge will become compressed and joint movement will be limited. Eventually the joints will have to be restored through a process involving cutting away part of the approach pavement and replenishing filler extruded by prior joint compression.

No single-joint design is available to accommodate these movements suitably, so ODOT engineers say that they prefer to use the simple pressure relief joint because it is the only one that can be easily maintained by state maintenance personnel. Other, more complex designs now available do not function well and are difficult to repair and in many cases have to be replaced.

RESEARCH

Extensive research on passive pressure is needed to describe both the relationship between the amount of soil compression and the generation of passive pressure and the effect of alternating cycles of soil compression and expansion. Until such research has been accomplished, present integral bridge design procedures will depend on idealizations and simplifications that probably do not accurately predict passive pressure effects.

Shrinkage and creep studies are needed for both integral bridges and their jointed bridge counterparts. Although present research in this area has been illuminating, the numerical procedures presently recommended do not properly account for the composite behavior of various combinations of beam and slab sizes. Also, the results of recent computer studies have not been verified by comprehensive physical testing nor been presented in a form suitable for use by practicing design engineers.

The lack of comprehensive research on passive pressure is probably responsible for the lack of specifications to guide the development of suitable designs for integral bridges.

SUMMARY

As the above enumerations have shown, integral bridges have numerous attributes and few limitations. Because design provisions can be made to account for some of these limitations (cycle-control joints, pressure-relief joints, approach slabs, construction procedures, and structure buoyancy), only application limitations (structure length, curvature, skew, overburden depth, and unstable subsoils) should negate the use of integral bridges in favor of their jointed bridge counterparts. In many areas of the country, integral bridges are being used whenever application limitations do not prevent their use. The high abutment pile stresses and uncertain passive pressure effects are being accepted as the only negative aspects of such designs. However, these negative aspects are acceptable whenever they are weighed against all the attributes that integral bridges provide.

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