TITLE: COST EFFICIENT AND INNOVATIVE BRIDGE APPROACH SLAB DESIGN

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Abstract

Concrete bridge approach slabs (BAS) are used at the interface between bridge abutments and pavements that rest on compacted embankment. The objective of this research was to develop optimal cost BAS designs for new and replacement slabs. Two solutions presented here include a cast in place (CIP) design for new construction and novel precast prestressed slab (PCPS) designs for new construction and replacement of BASs. Practices of different US state Departments of Transportation (DOT) for BASs were evaluated and compared to the current practices of Missouri DOT (MoDOT). Based on the practices, a twenty feet span was chosen and finite element models were analyzed considering different slab lengths, thicknesses, and loss of support conditions to calculate maximum moments, deflections, and end slopes. Based on predicted values, CIP and PCPS design alternatives were recommended. Recommended alternatives are estimated to have a lower cost, and an equal or better performance compared to the current MoDOT designs. Currently a new study has been initiated where the recommended BAS designs are being implemented in the field.
INTRODUCTION

A bridge approach slab (BAS) is a reinforced concrete slab used at the interface between a bridge abutment and the pavement on compacted embankment. The BAS provides a smooth transition from the abutment, typically supported by a deep foundation, to the pavement on compacted embankment with higher settlement potential. Every US state Department of Transportation (DOT) has its own practice for design and construction of BASs, and settlement of BASs has been a major problem in all of the states. Thirty five percent of the BASs in the US were reported to have experienced some sort of failure (1). A study performed in 2002 ranked BAS settlement as the second most significant problem in Missouri after slope stability issues (2).

Different studies in the literature agree that BAS settlement is affected by geotechnical and structural factors (3). Erosion of soil due to inadequate drainage near the abutment and consequent void formation under the BASs was reported to cause longitudinal cracks on BASs (4). Movement of abutments due to temperature and traffic loads and loads due to creep and shrinkage were also reported to cause cracks on BASs (5). A study on general BAS settlement in Iowa observed that 25% of the 74 examined bridge sites had severe void development problems (3). The study reported that void development tended to occur in the first year of the BAS construction and concluded that approach pavement systems were performing poorly because of poor backfill properties, inadequate subsurface drainage, and poor construction practices. Another study in Iowa proposed BASs to be designed based on the length of observed voids and recommended a 15 ft long simply supported beam design for BASs (6).

Although there is no national design, service life, or performance standard for BASs, different studies in the literature proposed service limits based on the differential settlement and the end rotations of the BASs. Differential settlement is defined as the difference between the vertical displacements between the two ends of the slab. The end rotation, $\theta$, is the differential settlement divided by the length of the slab. A BAS rating system proposed in 1998 defines a 1 inch settlement as a bump, a 2 inch settlement as a moderate bump, and a 3 inch or larger settlement as a significant bump requiring repair and rehabilitation (7). In terms of end rotations, a slope change less than $1/200$ radians was found acceptable for riding comfort and a slope of $1/125$ radians or greater was found to cause riding discomfort (8).

Finite element analysis approach was used in the literature to analyze the behavior of BASs (9, 10). A 3-D finite element model was used to evaluate the performance of a BAS at different embankment settlement levels considering the interaction between the BAS and the embankment soil. Internal moments predicted using the model provided the design engineers with a scientific basis to properly design the BAS (11).

The study presented in this paper also used finite element analysis to evaluate the two different current BAS designs being used by Missouri DOT (MoDOT) and to propose new, innovative, cost effective BAS designs that can readily be implemented in the field. The initial step was to conduct a nationwide survey among state DOTs to evaluate different BAS designs currently being used, their performance, and their costs. It should be noted that in the current economic environment where state DOTs are trying to maintain and construct transportation structures with diminishing funds, the cost of proposed designs is extremely important if they are to be implemented. In addition to the survey, a number of bridges with deteriorating BASs in Missouri were investigated. Embankment erosion of 6 to 8 inches underneath the slab at the abutment end, longitudinal cracking, minor transverse cracking, and differential settlement in the order of $\frac{1}{2}$ to 1 inch were observed. Based on the information obtained from the survey, site visits, and through discussions with MoDOT officials, new BAS designs with different lengths, depths, load combinations, and assumed void formations were analyzed. Based on predicted deflections, end rotations, and moments, cast-in-place (CIP) and precast/prestressed (PCPS) design alternatives were recommended. Recommended alternatives are estimated to have a lower cost, and an equal or better performance compared to the current MoDOT designs.
**Survey Results**
A survey instrument, consisting of six basic questions, was developed and distributed to state DOTs to assess the design and performance of BASs in their region. Twenty states responded to the survey. Among the respondents, Montana was the only state that did not routinely use a BAS. While 42% of respondents reported frequent problems with their BASs, 83% reported minor cracking and 17% reported extensive cracking of BASs. Embankment settlement issues were reported by 79% of respondents and again 79% reported requesting special backfill materials for BASs. When asked, if they were satisfied with their overall BAS design, 68% responded positively. Results indicated that states were using BASs with span lengths varying from 10 to 33 ft and depths varying 8 to 17 inches. Among the responding DOTs 37% was using a span length of 20 ft and 33% used a depth of 12 inches. Based on geometric parameters and amount of steel, the design moment capacity of each state BAS was calculated (assuming singly reinforced sections). The design moment capacities varied largely among the states from 18 to 120 ft-kips/ft.

MoDOT currently uses an integral standard BAS design with a span length of 25 ft and depth of 12 inches on all major routes. The bottom longitudinal and transverse reinforcement used are #8 at 5 inches c/c and #6 at 15 inches c/c, respectively. The top longitudinal and transverse reinforcement used are #7 at 12 inches c/c and #4 at 18 inches c/c, respectively. The slab is connected to the abutment using mid height #5 bars at 12 inches c/c and it rests on a sleeper beam on the pavement side. The design moment capacity of MoDOT BAS was calculated to be 69 ft kips/ft. Using MoDOT unit costs, extracted from recent BAS projects, the cost of a 38 ft wide, 25 ft long, and 12 inches deep standard MoDOT BAS was estimated to be $55,316. It was observed that 50% of the total cost was materials cost, of which 37% was the cost of reinforcement. The cost of formwork and base preparation were 8 and 4%, respectively. Cost of BAS designs of all the states in the survey was performed using the MoDOT unit costs as shown in Figure 1. Compared to other states the cost of MoDOT standard BAS design was found to be on the higher end and most of the states with lower cost were using a span length of 20 ft and a depth of 12 inches. Detailed information on the survey and its results can be found in the recently published MoDOT research report (12).

**NUMERICAL MODELING**

**Cast in Place (CIP) Solution**
BAS can either be designed as a simply supported beam or as a slab on grade. Slab on grade approach can lead to an unconservative design whereas the simply supported beam approach can lead to an uneconomical design. The American Association of State Highway and Transportation Officials (AASHTO) code does not provide strict guidelines for designing an approach slab (13). AASHTO’s Load and Resistance Factor Design (LRFD) manual for highway bridges provides specifications for a simply supported bridge deck (14). In this study, initially three different design approaches were evaluated; Allowable Stress Design (ASD), Load Factor Design (LFD), and the LRFD approach. Span lengths from 15 to 25 ft in increments of 2.5 ft were evaluated along with a depth variation from 12 to 16 inches. One salient observation was that the LRFD approach consistently required the same amount of steel as the LFD approach; however the steel required by the ASD approach was significantly higher compared to these approaches. Considering cost analysis of the designs with MoDOT unit costs and results of the state of the art survey, a BAS design with 20 ft span length and 12 inch depth was selected for analysis with finite element models.

Although the selected design had a span length of 20 ft, considering that MoDOT would also need a 25 ft design to replace deteriorating existing BASs, two finite element models of 20 and 25 ft span were constructed. Soil support conditions under the slab were modeled using elastic springs. Soil support conditions were changed from full support state to a void formation state where voids reached up to 25% of the span length from the abutment end. Considering the two different span lengths and five boundary conditions a total of 10 cases were analyzed. The five boundary conditions were:
1. Simply supported BAS
2. Slab on grade with no voids
3. Slab on grade with voids 15% of the span length
4. Slab on grade with voids 25% of the span length
5. Slab on grade with no sleeper slab (pinned at the abutment end)

SAP 2000 V12.0.1 was used to model the BASs (15). A 3D finite element model was developed using four-node shell elements with defined layers of reinforcement. The mesh size used in the model was of size 1 x 1 ft. The total number of nodes and shell elements for the 20 ft model were 819 and 760, respectively. For the 25 ft model the corresponding numbers were 1014 and 950. Both top and bottom longitudinal and lateral bars were incorporated in the model. The slab-abutment interface and the slab-pavement interface were modeled as pinned connections except for the boundary condition without a sleeper slab, where the slab was only pinned at the abutment end. Concrete compressive strength was assumed 4000 psi. Values of modulus of elasticity (MOE) and modulus of rupture ($f_r$) were calculated from the compressive strength using the American Concrete Institute (ACI) equations to be 3605 ksi and 474 psi, respectively. Poisson’s ratio for concrete was assumed 0.2 and the grade of steel was defined as 60,000 psi. The nonlinear material model for concrete available in SAP 2000 was used in the analysis. A poor soil support condition with a subgrade modulus of 18.4 lb/in$^3$ was used in the model, which based on the 1 ft$^2$ mesh size corresponded to a spring stiffness of 220.8 lb/ft.

The standard design truck HS20-44 with three axles and a gross weight of 72 kips was used along with the design lane loads to load the model. The tandem load was also considered along with the lane load. The design truck was 6 ft wide and the distance between front axle and middle axle was 14 ft. The distance between middle and rear axle was varied from 14 to 30 ft and 14 ft was chosen considering the span of the slab for further evaluation. The design lane load consisted of a uniformly distributed load of 0.64 kips per linear foot along the span and distributed transversely over a 10 ft width. The load was applied as pressure on 1ft$^2$ elements. The pressure load under each axle for every wheel was calculated to be 12.5 ksf for tandem and 16 ksf for truck load. The slabs modeled here could accommodate 3 traffic lanes. Because only two axles could traverse on the slab at a time, two axles with point loads of 32 kip were used. The design truck and the design tandem load were positioned to produce extreme force effects. Load combinations considered were:

1. Strength Load Combinations:
   a. 1.25*DL+1.75*1.33*Tandem load+1.75*lane load
   b. 1.25*DL+1.75*1.33*Truck load + 1.75*lane load

2. Service Load Combinations:
   a. DL +Truck + Lane load
   b. DL+ Tandem + Lane load

Precast Prestressed (PCPS) Slab Solution

After examining PCPS BAS demonstration projects reported in the literature, a PCPS BAS design was also included in the study. The Texas DOT completed a PCPS BAS project in 2002 on I-35 frontage road in Georgetown, TX and the California DOT constructed a PCPS BAS in 2004 on I-10 in El Monte, CA. These projects were followed in 2007 by Iowa DOT PCPS BAS project on Highway 60 (16). The final reported cost of the Highway 60 project, approximately $739/yd$^2$, was much higher compared to the cost of cast in place BAS in Missouri, approximately $280/yd^2$. Because of many inherent advantages of PCPS BASs, such as fast installation, improved performance, and durability, the researchers analyzed and designed an innovative PCPS BAS solution that can be built for a comparable price as the proposed cast in place solutions.

A 38 ft wide BAS with three lanes was proposed to be constructed using 5 PCPS panels; 4 panels of 8 ft width and 1 panel of 6 ft width. Similar to the cast in place designs, 2 BASs with 20 and 25 ft span lengths were designed for new construction and replacement applications. The design included a 2 inch
asphalt overlay above the 10 inch deep panels for both lengths. Asphalt overlay decreased the finishing cost of PCPS panels, facilitated matching the crown layout of the bridge deck, and provided a smooth transition from the abutment to the BAS that could easily and cost effectively be fixed in case of future differential settlement.

**ANALYSIS OF RESULTS**

**Cast in Place (CIP) Solution**
The design lane loads that were discussed in the numerical modeling section were considered for all the models to represent the AASHTO notional load concept. However, because the considered BAS span lengths are shorter than the used standard HS20-44 truck, it was decided that the lane load could be excluded from the design. It is very unlikely that both lane loads and truck loads would be simultaneously present on the BAS. The finite element models were evaluated for both cases, with and without the lane load, to evaluate its effects. Table 1 shows the moments and deflections for the 20 and 25 ft long slabs considered in the previously listed five boundary conditions, with and without lane loads.

Results indicate that for the simply supported case (boundary condition 1) moment demand was decreasing significantly (approximately 50%) for both span lengths. Increasing the voids under the BAS from none to 25% of the span length (boundary condition 2 to 4) increases the moment demand for both conditions, with and without lane loads. It should be noted that without the lane loads the moment demand is lower than 40 ft-kips/ft for all boundary conditions except the simply supported case. The deflections shown in Table 1 are for the worst case condition of service loads. Similar to moments, there is approximately a decrease of 50% in peak deflection for the simply supported case (boundary condition 1) between the cases with and without lane loads. The highest peak deflection value is 0.63 inches for the simply supported case with lane loads and this value is lower than 1.5 inches, which would be the serviceability limit based on the recommendations reported in the literature (8). Evaluation of slopes (end rotations) for the worst case condition of service loads show that the maximum slopes will be 0.42 and 0.204 degrees for the 25 ft span with and without the lane loads, respectively. Maximum slopes for the 20 ft span are 0.27 and 0.14 degrees with and without the lane loads, respectively. These values indicate a decrease in the slope values of approximately 50%. The maximum slope for the 20 ft span with 25% voids (boundary condition 3) was 0.17 degrees which is lower than 0.286 degrees, which is the serviceability limit based on the 1/200 radian criterion.

**Precast Prestressed (PCPS) Slab Solution**
A systematic computer based analysis was conducted using SAP2000 v.12 (15). The matrix of cases consisting of different span lengths and boundary conditions was similar to the one used for the cast in place analysis. In addition to the 5 boundary conditions evaluated for the cast in place design, a sixth boundary condition was evaluated for PCPS case, where the length of voids was increased to 50% of the span length.

Results indicated that the moment demands were 33.8 and 39.6 ft-kips/ft for the 20 and 25 ft BASs, respectively. These values were considered without including the lane loads, with an assumed soils subgrade modulus of 175 psi/in, and voids as long as 50% of the span length at the abutment. Simulations showed that the peak moments were concentrated in the central region and tapered off towards the ends. Based on these observations and analysis, it was decided to design the PCPS BAS for a factored moment of 40 ft-kip/ft.

**RECOMMENDED DESIGN AND COST ESTIMATES**

**Cast in Place (CIP) Solution**
The area of main reinforcement required for the observed demand moment of 29.4 ft-kips/ft (Table 1, Boundary Condition 4) is 0.72 in^2/ft of BAS width. The main recommended reinforcement consisted of #6 bars at 5 inch c/c having an area of 1.06 in^2/ft of BAS width. The calculated design moment capacity
considering singly reinforced section was 37.3 ft-kips/ft of BAS width. Table 2 shows the cost breakdown for the current MoDOT BAS and the recommended BAS. It should be noted that the prices shown on the table do not include the overhead and profit, which were estimated to be 5 and 10.5%, respectively. The total cost of the recommended BAS including the overhead and profit was $55,316. Figure 2 shows the final design details of the proposed cast in place BAS.

**Precast Prestressed (PCPS) Slab Solution**

Figures 3 and 4 shows the final plan view and cross sectional view of the design details of the proposed 6 or 8 ft wide PCPS panels, respectively. The design of strands was performed using SAP2000 v.12 and the moment capacity was calculated to be 40.65 ft-kips/ft. The moment capacity was calculated based on strain compatibility, and the shear capacity, which was 224 kips at the ends and 101 kips at the center. The main purpose of the top layer of strands is to provide negative moment reinforcement against soil heaving and to account for stresses that can develop during stripping, hauling, and erection operations. Top reinforcement would also prevent excessive camber.

To facilitate construction and zero moment transfer the PCPS panels were designed to be connected to the abutment using dowel bars. Dowel bars were anchored to 6-8 inch deep holes drilled into the abutment with an adhesive/epoxy system. The design of PCPS panels contained 2 inch diameter holes with a spiral conduit for the dowel bars that could be filled with a non-shrink grout. The PCPS panels were designed to be connected in the transverse direction using 1 inch diameter continuous tie rods with 6 inch threads at the ends. The PCPS panels contained 3 inch diameter tie rod holes at ¼ span locations and the panels to be placed at outer edges of the BAS contained built in recesses (5 x 5 x 1.5 in deep). The design called for a backer plate to be used against the panels to tighten the tie rods to one half of the tension specified for A325 bolts per Missouri Standard Specifications. The recesses were to be filled with non-shrink grout after tensioning of tie rods. The PCPS panels were designed with keyways on the sides to ensure vertical alignment of PCPS panels, to possibly help with load sharing, and to ensure watertight joints. The design also called for a two layers polyethylene sheet to be placed between the PCPS panels and the aggregate base to decrease friction. Currently MoDOT typically places a 3 inch deep graded aggregate base under BASs.

In collaboration with Missouri precast manufacturers, the cost of the designed PCPS BAS was estimated to be $17.25/ft², including the delivery costs to a site within 100-150 miles of the precast plant. It should be noted that using the 20 ft span length BAS would increase the length of the pavement to be placed on both sides of the bridges. For the assumed 38 ft wide case, the cost of the additional pavement placement on both sides was estimated to be between $1,700 and $3,375 per bridge. Based on these estimates, the total cost of the proposed PCPS BAS was estimated to be between $46,839 and $48,514, which is lower than the cost of the standard MoDOT cast in place BAS. The cost of sleeper slab was not included in the analysis, assuming it will be the same for both cases.

**SUMMARY AND CONCLUSIONS**

The design recommendation for new slabs is a cast in place 20 feet in span and 12 inches thick with a sleeper slab for major roads. The expected deflection and slope for the considered 25 % void formation are within their allowable limits.

Precast prestressed slab with transverse ties have also been proposed. Detailed cost analyses have been performed for the proposed solution. From the cost observations it is evident that these slabs could be cost effective in new construction as well. Hence, designs for both a 20 foot span (new construction) and 25 foot span (old/replacement construction) have been proposed. Sleeper slabs are recommended for both designs. It has been shown by a cost analysis that the proposed precast solution ($46,839-$48,514) compares equally with the proposed cast in place solution ($47,893) and can be adopted for new construction as well resulting in considerable time and user cost savings.

The bridge approach slab recommended by this research cuts down almost 22% of the cost of construction compared with the current MoDOT BAS cost ($47,893 – Table 2) of construction. It should be noted that elastic soil support has been considered in designing the BAS and is the basis of this...
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recommended design. Lane load in combination with the Truck or Tandem load is not included in the final design. This exclusion is justified based on AASHTO-LRFD provision 3.6.1.3.3 which allows for decks and top slabs of culverts to be designed for only the axle loads of the design truck or design tandem for spans less than 15 feet (for a washout of 50% the effective span is at 10 feet). Further research is recommended to develop reliability based methodology for bridge approach slabs supported at the ends and by soil in between.

ACKNOWLEDGEMENTS

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<table>
<thead>
<tr>
<th>Span length (ft)</th>
<th>Boundary Condition</th>
<th>With lane loads</th>
<th>Without lane loads</th>
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<tr>
<td></td>
<td></td>
<td>Moment (ft-kips/ft)</td>
<td>Deflection (in)</td>
<td>Moment (ft-kips/ft)</td>
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<td>1</td>
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TABLE 2 Cost Comparison of the Current and Recommended Designs

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<td>Missouri BAS (25)</td>
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<td>Recommendation (20)</td>
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