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COST AND PERFORMANCE OPTIMIZATION OF PRECAST POST TENSIONED PRE-STRESSED GIRDER BRIDGE SUPERSTRUCTURES

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ABSTRACT

Bridges are the most costly components of a road transportation network. Pre-stressed concrete girders with cast in place concrete decks are widely used for short to medium span bridges. The design and subsequent cost of a bridge depends on key geometric variables such as bridge width, number of lanes, number and length of spans, slab thickness, number and spacing of girders. Some of these variables are dictated by traffic demands and highway geometry, while others are related to structural demands. Typically, designing a bridge usually involves experience and expert judgement of the bridge engineer. This study is aimed at cost and performance optimization of pre-stressed concrete girder bridges using a parametric study of the design variables and their effects on cost and performance of the bridge. A spreadsheet is developed for analysis and design of deck slab and girders using one dimensional beam line analysis and AASHTO LRFD distribution factors. The spread sheet also calculates the overall cost of the bridge superstructure. This spreadsheet is then used to perform a parametric study by iterating through all design parameters. It is shown that, contrary to conventional wisdom, the cost and performance of bridge superstructure are not necessarily competing factors. Relationships for slab thickness and girder spacing are presented that result in optimal performance and cost of the bridge superstructure.

KEYWORDS: *Girder Line Analysis, bridge design, cost and performance optimization*

INTRODUCTION

The development of national economy heavily relies on the transportation system of a country. Commerce, public transport, freight and communications etc. all are directly or indirectly affected by the quality of the transportation system. Bridges form a vital part of the transportation system and are quite the most costly component as well. The cost of bridge per unit length is several hundred times greater than that of the roadway part. In Pakistan, precast pre-stressed concrete bridges are widely used for short and medium spans (5-50 m span) due to their low initial cost, minimum maintenance, fast and easy construction and minimum traffic disruption. Their simple design, minimal depth-span ratio, assured plant quality and durability, in addition to desirable aesthetics, are added reasons for their wide application in the bridge industry. Nearly all highway bridges in Pakistan have been built utilizing standard precast pre-stressed girders with a cast-in-place deck that provides composite action with the girders. Engineers mostly perform the design of the precast pre-stressed girders using an empirical method using a trial and error procedure that is based solely on the experience and judgment of the bridge engineer. Due to rapid development in computing technologies and the advent of modern computational tools, the cost and performance optimization can be explored for large components of an infrastructure system like bridges[1].

A review of articles pertaining to cost optimization of pre-stressed concrete bridge structures is presented by Hassanain and Loov[2]. From this paper, it can be noted that very few studies have been performed towards the optimum design of the I-girder bridge structures considering the total cost of materials, fabrication and installation. A cost optimization study is performed by Sirca and Adeli[3] on pre-tensioned precast I-beam bridges taking different variables into account. Similarly Aydin and Ayvaz[4] used hybrid genetic algorithm for overall cost optimization of pre-stress concrete bridge and used cross-sectional dimensions as their design variables. Chang et al.[5] performed a parametric study for cost optimization of box girder concrete bridges. They used a spreadsheet for design and cost calculations.

The prime concern in a developing country like Pakistan, is the economy of the projects and their reliability, both in terms of initial construction and long term maintenance. This requires that the design of

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highways in general and that of bridges in particular, be performed such that efficient use of resources is assured. The approach currently in use is based on the engineer's own judgment and on trial and error; with no guarantee of obtaining the most economical girder choice or the minimum pre-stressing force required to meet the design conditions for such girders. To address these challenges, this research was conducted with the following objectives:

- To assess and revise the existing design procedure used for the design of pre-stressed girders, instead of using the usual method of trial and error;
- To develop guidelines for selecting the deck slab thickness for optimal load distribution to girders and reduce overall cost of bridge superstructure;
- To develop guidelines for optimized selection of pre-stressed girder cross-sections and its spacing that is most cost effective and best in performance and to find the exact pre-stressing force and eccentricity required to fulfill the design criteria.

It should be noted that this study is limited in scope to only simply supported spans of precast post tensioned pre-stressed concrete girder bridges with cast in place concrete decks. Furthermore, the scope is restricted to the superstructure only and the choice of spans is treated as an independent variable because that is primarily guided by factors such as terrain, geological, geotechnical and hydrological conditions of the site, and availability of technological and construction resources.

METHODOLOGY

A simply supported span of the type of bridge under study in this article was selected as the basic model to test all the variables in the subsequent section. An elaborate excel spreadsheet was developed to analyze and design the bridge with given design parameters. The bridge geometry, girder selection and material properties are specified in the spreadsheet which then performs a beam line analysis of the bridge and calculates:

- Composite section properties for interior and exterior girders
- Live and dead load force effects using AASHTO LRFD[6] HL-93 specifications [A3.6.1.2.1]
- Distribution factors for moments and shear are calculated using AASHTO[7] A4.6.2.2.2 specifications
- Design of the pre-stress girder including the proportioning of pre-stress steel cables, their eccentricity and required pre-stressing force
- Quantity estimation of concrete in all components including the girder (at end blocks, I sections and transition zones), deck slab, diaphragms and curbs, as well as quantities of mild reinforcing steel and high strength pre-stressing steel, sheath pipe and anchorage devices.
- In addition to estimating the above quantities, the spreadsheet also calculates other costs such as launching of girders, stressing of tendons, injecting of cement grout in tendons and cutting off projecting ends

In addition to calculating the cost of the bridge super-structure the spreadsheet also calculates performance indices as described in the later sections. This sheet was then used to perform parametric study by varying each parameters and calculating the performance indices and cost of the bridge super-structure. The spreadsheet had macros programmed in to help create relationships between various parameters and their effect on cost and performance of the bridge.

Validation of the Spreadsheet

In order to validate the use of AASHTO LRFD beam line method and analysis performed by the spreadsheet, a number of finite element models of varying geometry were also analyzed in SAP 2000® and the results were compared. Figure 1 shows the comparison of moments calculated by Beam-Line Analysis performed by the spreadsheet and those calculated using SAP 2000.

The above results show that in case of interior beams, the AASHTO LRFD Distribution Factors give conservative and very close results to that of Finite Element Method (96-99%). For exterior girders they give relatively more conservative result for shorter spans (83-90% doe

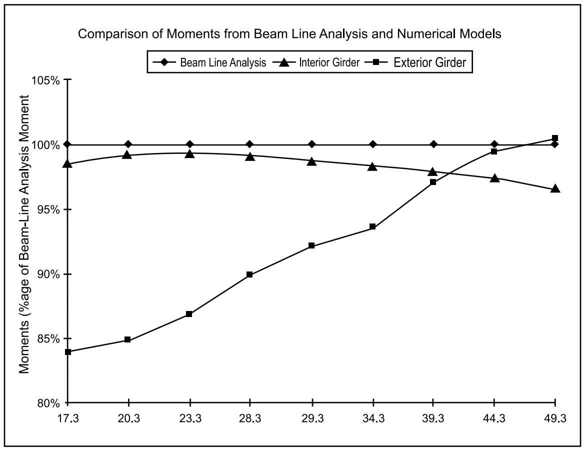

Figure 1. Comparison of Moments from Beam Line Analysis calculated by the spreadsheet and Numerical Model in SAP2000.

spans less than 25m) but as the spans become longer they tend to become relatively less conservative. Although, beam-line analysis underestimates the moment for exterior girder for spans longer than 50m, however, within 50m range, the moments given by beam-line method can be used reliably for the design.

Cost of the bridge super structure

The major components that affect the cost of the bridge were selected on the basis of parametric study performed on all variables. The following variables were selected for their effect on cost and performance of pre-stressed concrete post tensioned bridges for parametric study:

The Girder Cross-Section

There is nearly infinite variety of girder cross-sections that can be used in the super structure of pre-stressed concrete bridges. However, only first four of the standard I sections (Types I-IV)) recommended by AASHTO LRFD, are used in this study.

Slab Thickness

Slab Thickness is a very important parameter which has a great effect on both the cost and performance of the bridge. The slab thickness not only contributes to the major part in the cost of the bridge, but also has a great impact on the distribution of loads on to the girders. If the slab is thick and rigid, it will be very costly but it will require less amount of reinforcing steel and also it will distribute the loads to the girders more evenly, thereby reducing the demand on each girder. This in turn, not only increases performance but also reduces cost of the girder. On the other hand, a thinner slab, may reduce the cost of the deck, but will cause the deck reinforcement to be increased, and will not distribute the loads evenly to all girders, thereby increasing the demand on each individual girder and consequently increasing the girder cost.

Girder Spacing

Girder spacing is the most important variable that affects the performance of the bridge system and consequently its cost. In this study, the bridge width is kept constant, because it is controlled by the site conditions, so the girder spacing will actually control the number of girders and width of the overhang.

Number of Girders

This parameter although effects the cost and performance to a great extent but it is controlled by the width of the bridge and the spacing of the girders. Hence, this variable is not treated as an independent variable.

Performance of the bridge

Optimization of any engineering system does not only involve minimizing the cost but also involves maximizing the performance. In case of pre-stressed girder concrete bridges, we observe that the cost and performance are not always competing factors, rather sometimes, they may complement each other.

Following are the two performance indices selected for this study:

Newmark's H-Parameter

A dimensionless stiffness parameter H establishes the relative girder-to-deck stiffness and offers a direct measure of the performance of the bridge system[8]. The H parameter is given by the equation:

$$H = \frac{E_g I_{cg}}{\left(\frac{L E_s t_s^3}{12(1-\mu^2)} \right)} \tag{1}$$

where, I_{eg}= Moment of inertia of the composite girder;

E_g= Modulus of Elasticity of the girder material;

E_s= Modulus of Elasticity of the deck slab material;

μ= Poisson's ratio of the slab's material;

t_s= Thickness of the deck slab;

Obviously, the relative stiffness of girders and deck plays a very important role in the overall performance of bridge superstructure, especially considering the performance over a long period.

Additional Moment Capacity

Usually, all civil engineering structures are so designed that they fulfil the required strength criteria with minimum cost. This is largely true for linear problems like building design or for design of individual components where increasing the strength capacity means increase in cross-sections that raises the cost as well. However, when the performance of overall system is considered, especially the relative stiffness of components that act together to provide the strength resistance, then it is possible to reduce the cost significantly by increasing the size of one component (usually a cheaper one) and reducing the demand on other more expensive components. In this way, the overall system performance is improved due to more even stress distribution and may as well reduce the cost of the overall system. In this study we observed that reducing the cost of the bridge sometimes result in additional strength capacity. For optimization such designs are ideal and always favored. The additional moment capacity of the deck and girder system, which is over and above the required moment capacity is considered a performance index as well. Therefore, maximizing this index will result in a more robust and durable bridge design.

The objective function

For optimization of a system we require some performance index, or a quantity which can be used to rank or favor a particular solution as better from the rest. In the above sections we identified three such indices, namely the cost of the bridge, the relative stiffness or Newmark's H-Parameter, and additional moment capacity of a bridge. The problem is to minimize the cost and maximize the rest. The objective however, is to maximize performance and minimize the cost. We will first convert the cost minimization into some function to be maximized such that minimizing the cost maximize the function. This function can be combined with the performance index to get the single objective function to maximize. Such a function can be obtained by several means; including, multiplication of cost by -1, by taking the reciprocal of the cost or subtracting the cost from some maximum (unrealistic) cost.

The weighted sum of the three indices is used as the objective function for the optimization problem. The weights assigned here are subjective and may change on a case to case basis. In this study we use assigned 50% weightage to cost and 25% weightage each to the H-Parameter and additional moment capacity.

RESULTS AND DISCUSSION

Effect of Girder Spacing

Girder spacing is the most important parameter affecting the cost and performance of a bridge. This variable is usually coupled with number of girders and the total bridge width. It's optimum value invariably depends on the width of the overhang. If the width of the overhang is more than half the girder spacing, then dead and live load demand on the exterior girders will significantly increase as compared to the demand on the interior girders. In order to minimize this effect, a limit of half the girder spacing is proposed on the width of the overhang. With this limitation in place, the number of girders become a function of only the total bridge width and the girder spacing.

The effect of girder spacing on cost with different Total Bridge Width is plotted in Figure 2. It can be observed that the minimum cost spacing is the one which results in 4 girders, which is the minimum specified by AASHTO if beam-line analysis with AASHTO LRFD distribution factors are to be used. This minimum cost can be related to the Total Bridge Width by plotting this minimum value, resulting in a linear relationship

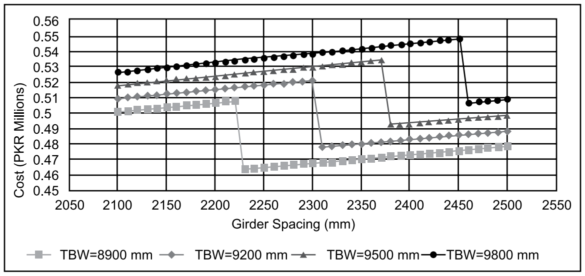

Figure 2. Effect of Girder Spacing on the cost of a 15-m bridge with varying Total Bridge Width

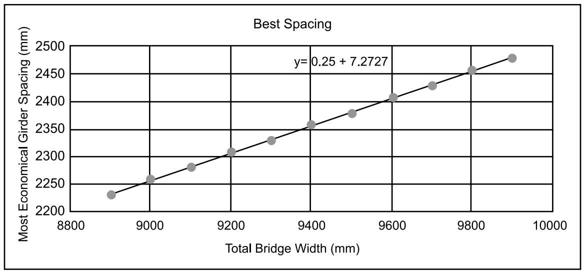

Figure 3. Most Economical Girder Spacing vs. Total Bridge Width for a 15m span using Type III Girder

shown in Figure 3.

The above linear relationship for optimum girder spacing is as follows:

$$S = 0.25\ TBW + 7.273$$

Where,

S = *Girder Spacing (mm)*

TBW = *Total Bridge Width (mm)*

Effect of Slab Thickness on Cost

Slab Thickness of the bridge is often governed by serviceability limit states, with minimum being 7 inches (180 mm) [A9.7.2]. To control the deflection, minimum slab thickness is based on deck span with main reinforcement parallel to the traffic [A2.5.2.6.3-1]. Most bridge designers often provide the minimum slab thickness. In this study the slab thickness was varied between minimum required by AASHTO LRFD and a maximum value of 350mm. The effect of variation in slab thickness on cost and performance of the bridge is shown in Figure 4 and Figure 5. It can be observed that increasing the slab thickness results in decrease in the overall cost to some extent, after which the cost increases linearly again. The minimum cost point of the slab is the optimum slab thickness in terms of cost. We, however, also observe that the same optimum slab thickness results in an optimum value of additional moment capacity for girders as well. This is in contrast to the conventional wisdom of cost

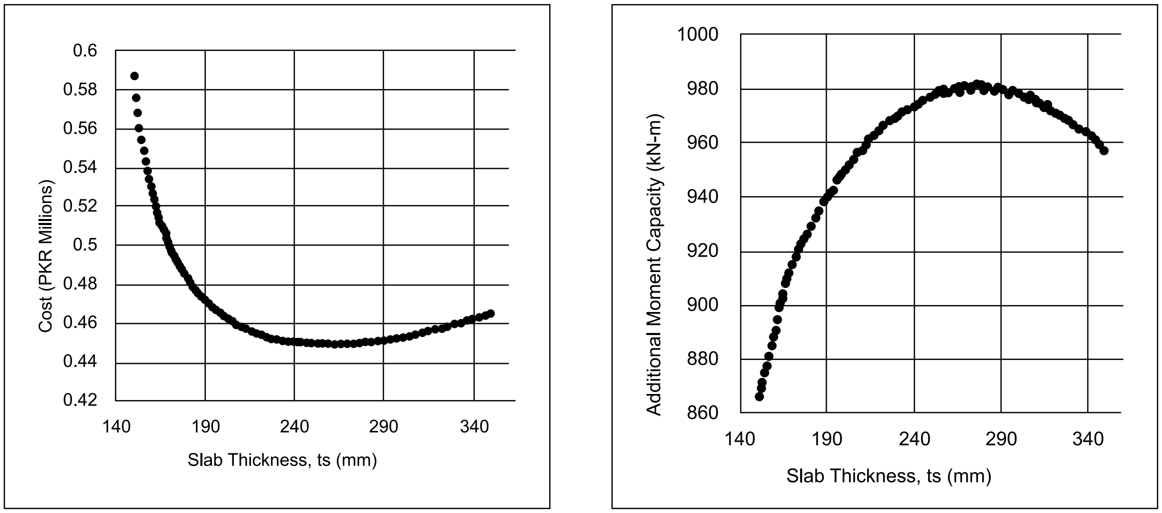

Figure 4. Cost (left) and Additional Moment Capacity of Girders (right) against varying slab thicknesses of a 2-Lane 15m Span with a total bridge width of 8.9m using a Type III Girder.

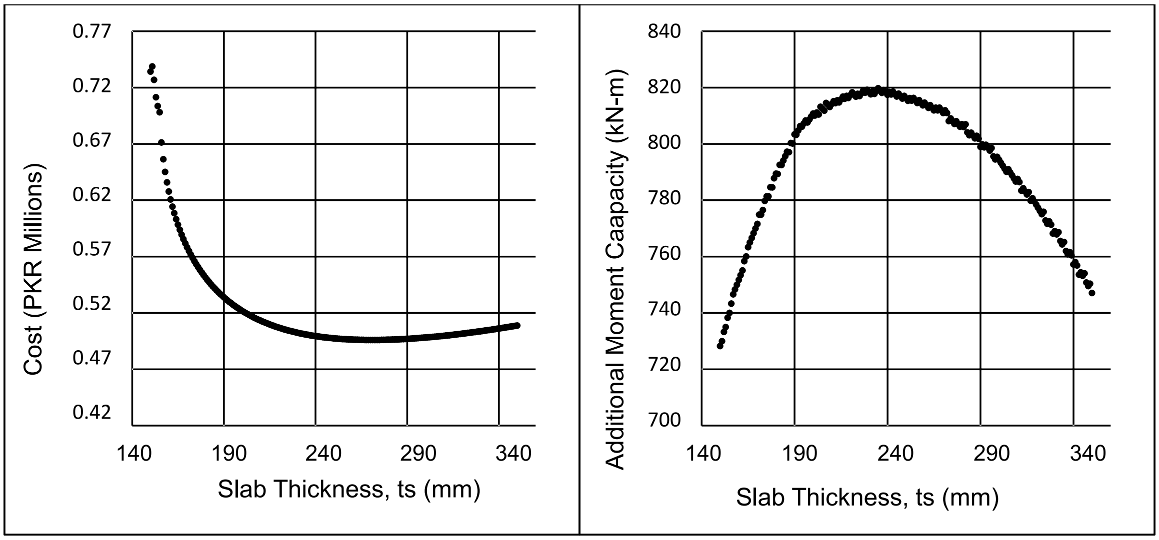

Figure 5. Cost (left) and Additional Moment Capacity of Girders (right) against varying slab thicknesses of a 2-Lane 15m Span with a total bridge width of 10.1m using a Type III Girder.

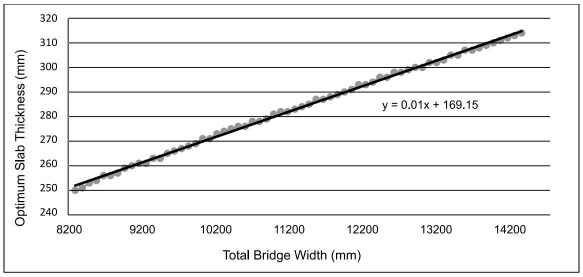

Figure 6. Optimum Slab Thickness vs. Total Bridge Width for a 15 m bridge with using Type III girder

being a competing factor to the performance.

Similar relationships were plotted for varying the total bridge width and the span length, and slab thicknesses corresponding to minimum/optimum cost were noted. The relationship of optimum slab thickness to total bridge width is shown in Figure 6.

The above plot results in the following relationship for optimum slab thickness.

$$t_s = 0.01TBW + 169.5$$

Where, Thickness of the slab (mm)

Total Bridge Width (mm)

CONCLUSIONS

Contrary to conventional wisdom the cost and performance of a bridge superstructure may not necessarily be competing factors. In-fact increasing the slab thickness leads to better performance as the slab becomes stiffer and provides good load distribution to the girders hence optimizing the load transferred to the girders and thus reducing the cost of girders which are very costly compared to the deck slab. The relationship obtained for slab thickness in parametric study is as:

$$t_s = 0.01TBW + 169.5$$

Where TBW is total width of the bridge deck.

The right girder spacing for an optimized design is quite a problem. In current design procedure, there is no provision for finding an optimized spacing. However, now we can find the optimized girder spacing for a given bridge, by performing a regression analysis on table. The least squares method for a linear regression gives the following expression for optimization of girder spacing.

$$S = 0.25TBW + 7.273$$

The above equation will always result in 4 girders. The most cost-effective number of girders given by this analysis will always be 4. However, greater no.

of girders can be used but that will increase the cost of the bridge. These are related to vertical clearance. Sometimes a greater number of girders are required to reduce total depth of the girders because of the vertical clearance restrictions or due to restricted space for the approach roads etc.

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