Engineering Structures 31 (2009) 1250–1264

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Live load distribution equations for integral bridge substructures

Semih Erhan, Murat Dicleli *

Department of Engineering Sciences, METU, Turkey

ARTICLE INFO

Article history:
Received 21 October 2008
Received in revised form
16 January 2009
Accepted 17 January 2009
Available online 12 February 2009

Keywords:
Integral bridges
Live loads
Load distribution
Abutment
Pile

ABSTRACT

In this study, live load distribution equations (LLDEs) for integral bridge (IB) substructures are developed. For this purpose, numerous 3-D and corresponding 2-D structural models of typical IBs are built and analyzed under AASHTO live load. In the analyses, the effect of various superstructure and substructure properties such as span length, girder spacing, girder stiffness, abutment height, pile size, pile spacing and foundation soil stiffness are considered. The results from the 2-D and 3-D analyses are then used to calculate the live load distribution factors (LLDFs) for the abutments and piles of IBs as a function of the above mentioned properties. LLDEs are then developed to estimate the live load moments and shear in the abutments and piles of IBs using these LLDFs and nonlinear regression analysis methods. It is observed that the developed LLDEs yield a reasonably good estimate of live load moment and shear in the abutments and piles of IBs.

1. Introduction

Structural analysis of highway bridges using complicated 3-D finite element models (FEMs) to determine live load effects in bridge components is possible due to the readily available computational tools in design offices. However, throughout the design process, using such complicated methods is tedious, time consuming and expensive. Therefore, most design engineers prefer using simplified 2-D structural models of bridges and live load distribution equations (LLDEs) available in current bridge design codes such as AASHTO (American Association of State Highway Transportation Officials) LRFD (Load and Resistance Factor Design) Bridge Design Specifications [1] to determine live load effects in bridge components. In AASHTO LRFD Bridge Design Specifications, LLDEs are available only for the girders of jointed bridges. AASHTO does not have any provisions for the calculation of live load effects in integral bridge (IB) components including the girders, abutments and piles. Consequently, these LLDEs are also used for designing the girders of IBs. In addition, most design engineers generally calculate the live load effects in the abutments and piles of IBs by using the AASHTO LLDEs developed for the girders of jointed bridges. This approach is based on the assumption that the same rotations about a transverse axis perpendicular to the longitudinal direction of the bridge occur both in the abutments and the girders under live load due to the monolithic construction of the superstructure-abutment joint in IBs. However, it is anticipated that the concentrated rigidity of a particular girder combined with those of the adjacent girders connected to the abutment having a smeared rigidity, may produce a live load distribution within the abutment and piles different than that calculated using the LLDEs developed for the girders of jointed bridges. Therefore, using AASHTO LLDEs may results in either conservative or unconservative estimates of the live load effects in the piles and abutments of IBs.

Although many research studies have been conducted on live load distribution among the girders of conventional bridges [2–11] similar research on IB abutments and piles are scarce. Only recently, Dicleli and Erhan [12] have conducted a limited research study on live load distribution in IB girders. Most research on IBs is concentrated on the performance of such bridges under thermal effects [13–18]. Thus, in this study, LLDEs for the substructure components of single-span IBs are developed to address the above mentioned uncertainties and to provide useful tools to the bridge engineering community at large for the design of IB abutments and piles under live load effects.

2. Research outline

To obtain LLDEs for IB abutments and piles, two (2-D) and three (3-D) dimensional FEMs of numerous IBs are built and analyzed. In the analyses, the effects of various geometric, structural and geotechnical properties are considered. The results from the analyses of 2-D and 3-D FEMs are then used to calculate the live load distribution factors (LLDFs) for the abutments and piles of IBs as a function of these geometric, structural and geotechnical properties considered in the analyses. Next, the behavior of the abutments and piles under live load effects is studied in detail

* Corresponding author. Tel.: +90 312 210 4451; fax: +90 312 210 4462.
E-mail address: mdicleli@metu.edu.tr (M. Dicleli).

0141-0296/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2009.01.020

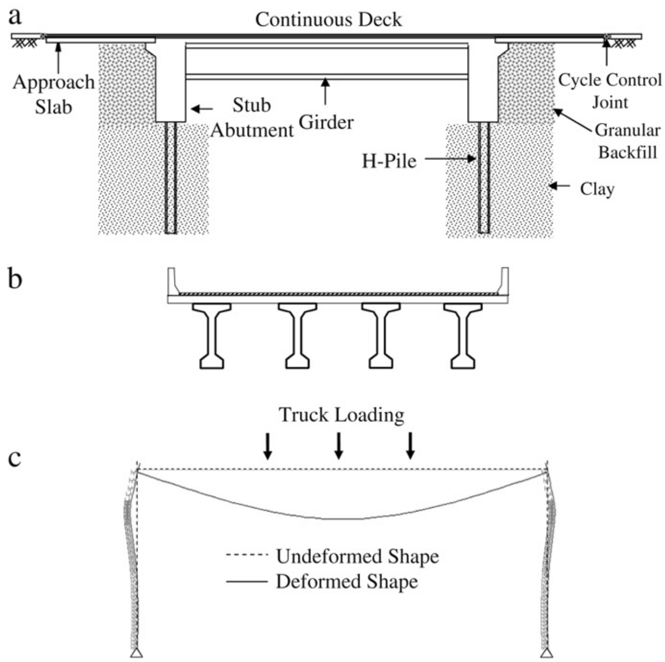

Fig. 1. (a) A typical single span IB, (b) Typical slab-on-girder bridge cross-section (c) Deformed shape of an IB under live load.

using the available analyses results. Subsequently, using nonlinear regression analysis techniques and the available analysis results, LLDEs are developed to estimate the live load moments and shears in the abutments and piles of single-span IBs. Finally, the obtained LLDE's are verified using the results from finite element analyses (FEAs).

3. Scope of the research study and assumptions

The research study is limited to symmetrical, single span slab-on-girder IBs with no skew (Fig. 1(a)). The IBs considered in this study are assumed to have AASHTO type prestressed concrete girders. Cross-section of a typical single-span IB with such girders is illustrated in Fig. 1(b). The abutments of IBs are assumed as supported by end-bearing steel H-piles typically used in IB construction. A moment connection is assumed between the piles and the abutment as well as between the superstructure and the abutment per current state of design practice [19]. Granular material typically used in IB construction is assumed for the backfill behind the abutments while cohesive soil (clay) is assumed for the pile foundations (Fig. 1(c)). Moreover, the scope of this research study is limited to short to medium length IBs where the superimposed dead load and thermal effects are assumed to be less significant compared to live load effects. Consequently, yielding of the piles is not anticipated under total load effects and the behavior of the backfill and foundation soil remains within the linear elastic range as proven by an earlier research study [12] due to the small lateral displacements of the abutments and piles under live load effects. This also ensures that potential formation of a gap behind the abutment due to cyclic thermal movements is negligible.

4. Bridges and parameters considered in the analyses

In an earlier research study [12] the IB superstructure and substructure properties that affect the distribution of live load moment and shear in the abutments and piles are identified. These parameters are; span length, girder size and spacing for the superstructure and abutment height, pile size, pile spacing and foundation soil stiffness for the substructure. Using these superstructure and substructure parameters, a number of IB models are built and analyzed to develop LLDEs for IB abutments and piles. For the superstructure, the span lengths of the IBs considered in the analyses are assumed as 15, 20, 25, 35, 40, 45 m. Furthermore, AASHTO prestressed concrete girder types; II, III, V and VI spaced at 1.2, 2.4, 3.6 and 4.8 m are considered in the analyses. A typical, 0.2 m thickness is assumed for the slab. The strength of the concrete used for the prestressed concrete girders is assumed to be 50 MPa while those of the slab and abutments are assumed to be 30 MPa. For the substructure, the abutments are assumed to be 2.5, 3, 4 and 5 m tall and supported by 12 m long end-bearing steel HP piles. The analyses are repeated for HP piles with the following sizes; 200×54, 250×85, 310×110 and 310×125. The assumed range of pile sizes is typical for IB construction. The spacing of these piles is assumed to be 1.2, 1.8, 2.4 and 3 m. In addition, the foundation soil surrounding the piles is assumed to be soft, medium, medium-stiff and stiff clay with an undrained shear strength of $C_u = 20, 40, 80$ and 120 kPa, respectively. The granular backfill behind the abutments is assumed to have a unit weight of 20 kN/m^3. The range of values considered for each parameter is given in Table 1. Seven sets of analyses are conducted as shown in the first column of Table 1. In each analysis set one of the parameters is considered to be dominant. For instance, in Analysis Set 1 while the span length is the main parameter, in Analysis Set 2 the girder spacing is the main parameter. For the main parameter, the full range of values considered is included in the analyses while the remaining parameters assume more limited range of values. In addition, the width of the IBs are considered as 12 m in Set 1 but 15.6 m in all the other sets to assess the effect of the bridge width (number of girder) on the distribution of live load in the abutments and piles. This resulted in more than 1200 different 3-D and corresponding 2-D structural models of IBs and more than 10,000 analyses for one design lane loaded case, two or more design lanes loaded case and for multiple truck positions in the transverse direction of the bridge.

5. Structural models of integral bridges

The 3-D and 2-D structural models of the IBs considered in this study are built and analyzed to calculate the LLDFs. The 3-D and 2-D structural models of the typical IBs used in the analyses are displayed in Fig. 2(a) and (b), respectively. Details about modeling of the superstructure, substructure and soil-structure interaction effects are presented in the following subsections.

5.1. Superstructure modeling for IBs

Literature review on finite element modeling of slab-on-girder bridges have revealed two comparative studies conducted by Mabsout et al. [6] and Yousif and Hindi [9] on finite element modeling of slab-on-girder bridges to select an accurate and practical finite element model (FEM). Four different FEMs of slab-on-girder bridges proposed by Imbsen and Nutt [2], Hays et al. [3], Brockenbrough [20] and Tarhini and Frederick [5] are compared in these studies. In the first model [3], the concrete slab is idealized as quadrilateral shell elements with six degrees of freedom (DOF) at each node and the steel girders are idealized as space frame members with six degrees of freedom at each node. The center of gravity of the slab coincides with the girders' center of gravity and the girder properties are transformed to the deck center of gravity (Fig. 3(a)). The second FEM is based on the research study of Imbsen and Nutt [2]. The concrete slab is idealized as quadrilateral shell elements and the girders are idealized using eccentrically placed space frame members. This model is similar to the first one but, rigid links are imposed to accommodate for the eccentricity of the