JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2017; X (X): 1–18

Available online at www.sciencedirect.com

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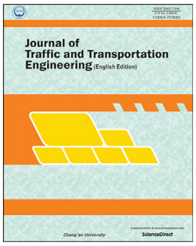
journal homepage: www.elsevier.com/locate/jtte



Original Research Paper

The optimal shapes of piles in integral abutment bridges

Q4 *Cheng Lan* [a], *Bruno Briseghella* [b,*], *Luigi Fenu* [c], *Junqing Xue* [b], *Tobia Zordan* [a]

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HIGHLIGHTS

- The horizontal stiffness of pile foundations in integral abutment bridges (IABs) has been investigated.
- A structural optimization technique is proposed to find the best solutions for pile foundations.
- The developed optimization method has been applied to a real 400 m-long IAB and a 500 m-long one.
- Different parameters have been analysed, including a) pinned or fixed pile head, b) pre-hole, c) pile diameter.

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Integral abutment bridges
Structural optimization
Concrete piles
FEM simulation

ABSTRACT

Integral abutment bridges (IABs) can be used to avoid the durability issues associated with bearings and expansion joints. For this type of bridge, the design of the optimal pile foundation, especially with respect to the horizontal stiffness, is a challenging issue. A structural optimization approach is proposed in this paper to optimize the pile foundation shape in integral abutment bridges. A procedure was implemented based on linking MATLAB, where an optimization code was developed, and OpenSees, which was used as the finite element solver. The optimization technique was compared with other techniques developed in previous researches to verify its reliability; the technique was then applied to a real 400 m-long IAB building in Verona, Italy, as a case study. The following two possibilities were considered and compared: (a) a pile with two different diameters along the depth and (b) a pile with a pre-hole. In fact, to increase the lateral and rotational flexibilities of the pile head, piles for an integral abutment bridge foundation are often driven into pre-deep holes filled with loose sand. Finally, the case of super-long integral abutment bridges ($L = 500$ m) with a corresponding displacement on one bridge end of approximately 50 mm was analysed. The following four pile design optimization cases were considered with similar study criteria as the Isola della Scala Bridge: (a) a pinned pile head for semi-integral abutment, (b) a fixed pile head without a pre-hole, (c) a fixed pile head with a pre-hole of any depth, (d) a fixed pile head of a pre-hole with a depth limit (<2 m) allowing for enough

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Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2017.11.001

Please cite this article in press as: Lan, C., et al., The optimal shapes of piles in integral abutment bridges, Journal of Traffic and Transportation Engineering (English Edition) (2017), https://doi.org/10.1016/j.jtte.2017.11.001

embedded length for the friction pile. The case studies confirmed the potential of the proposed optimization techniques for finding the optimal shape of piles in integral abutment bridges.

1. Introduction

Traditionally, expansion joints, roller supports, and other structural releases are used on bridges to prevent damage caused by superstructure expansion and contraction due to temperature variations, creep and shrinkage. Expansion joints and bearings increase the initial cost of a bridge and often do not function properly after years of service unless they are extensively maintained. Thus, integral abutment bridges (IABs), which have no expansion joints and bearings within the span or at the supports (Fiore et al., 2012, 2013), provide an alternative design (Briseghella and Zordan, 2015; Burke, 1993) Q1 that potentially offers lower initial costs and lower maintenance costs (Mahesh, 2005). IABs can be used for newly built bridges and to retrofit existing bridges (Briseghella and Zordan, 2007; Dong et al., 2014; Yannotti et al., 2005; Zordan and Briseghella, 2007). The monolithic connections between the deck and the sub-structure make IABs different from other conventional bridges and allows for a remarkably increased redundancy with improved response to seismic loading and other extreme events (Erhan and Dicleli, 2015; Xue et al., 2014; Zordan et al., 2011a). Furthermore, deck joints are known to be a continuing problem in existing bridges, due not only to their own failure and maintenance problems but also to the significant amount of corrosion damage in the girders and underlying substructures caused by run-off water containing corrosive de-icing salts leaking through the joints in the deck (Arockiasamy and Sivakumar, 2005). Presently, most European countries and U.S. states attempt to use IABs or semi-IABs for short-or medium-sized bridges (usually up to 100 m). The application of IABs based on their maximum length and the possibility to design super-long integral abutment bridges was investigated by several authors (Baptiste et al., 2011; Dicleli and Albhaisi, 2004; Zordan et al., 2011b).

However, soil-structure interaction problems due to thermal and long-term loads still represent a challenging issue requiring close cooperation between structural and geotechnical engineers.

According to several codes and guidelines for IABs, piles should be flexible under forces and moments acting on the abutment to settle horizontal movements, expansion and contraction induced by temperature variations, creep and shrinkage. Thus, the piles in IABs are often installed with their weak axis of bending resistance parallel to the bridge centreline (Greimann et al., 1987).

Design details for piles used in IABs were proposed in several studies (Franco, 1999). For example, studies completed in New York and Pennsylvania determined that piles should be designed for vertical and lateral loads; fixity between the superstructure and pile top is ignored. The Pennsylvania study also stated that piles should be analysed for bending induced by superstructure movements. Maine provided a step-by-step design procedure for piles. In North America, steel H-piles have typically been used in IABs to meet flexibility requirements, while in Europe and Asia, concrete piles are adopted (Gama and Almeida, 2014). Some states, such as Virginia, Pennsylvania and New York, allow the use of concrete encased-steel piles. Pennsylvania and New York specify that concrete encased piles shall not be used with spans greater than 150 feet (45.7 m). Virginia specifies the use of only concrete piles with a shelf abutment, similar to a spread footing on a set of piles. The majority of states in the U. S. specified orienting piles on their weak axis, perpendicular to the direction of movement (Wasserman, 2007). Two states specified using strong axis orientation, and other states had specific criteria for which orientation to use. For instance, New York related the use of axis to length of span (weak axis for spans less than 90 feet per 27.4 m, strong axis for spans greater than 90 feet per 27.4 m).

Typically the horizontal loads induced by the superstructure contraction and expansion are complicatedly distributed in the substructures due to the interactions of the soil-abutment and soil-pile (Burke Jr., 2009). The backfill earth pressure may take the larger proportion of the applied load (74%–88%), while the shear force at the top of the pile may take the small proportion (12%–26%) (Arsoy et al., 1999). This distribution might be caused by the geo-phenomenon of “ratcheting” (Horvath, 2004). Meanwhile, the displacement at the top of the pile nearly equals to the displacement at the top of the stub-type abutment. Therefore, the piles should be designed with the ability to accommodate a certain (lateral) shear force and large thermal-induced displacement.

Even if most codes indicate that flexible piles are better, it is not clear how to determine the optimal horizontal stiffness for a bridge and how to design the piles accordingly.

Therefore, a structural optimization tool to shape the piles used in integral abutment bridges according to the required flexibility is presented in this paper. The design optimization approach applied to find the optimal pile shapes is introduced in Section 2. The finite element (FE) modelling techniques used in the research and their verification based on previous research are described in Sections 3 and 4. In Section 5, a case study of an integral abutment bridge of 400 m built in Isola della Scala (Verona, Italy) is introduced, and the results are discussed. Finally, the conclusions are drawn in Section 6.

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