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Thermally induced soil structure interaction in the existing integral bridge

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ABSTRACT

While Cross' method enabled scientifically based structural design of integral bridges (IB) a similar progress in understanding and analyzing the relevant complex soil structure interaction has not been made yet. This hampers a wider adoption of IB systems, whose geo-structural system inherently brings multiple sustainability and performance benefits to transportation infrastructure. To this end, a full 3D finite element model of an existing three-span integral bridge was assembled and subjected to a combined thermal and gravity loads. The bridge superstructure consists of the two sets of concrete piers, two abutments, and fourteen HP steel piles (seven at each abutment), whose strong axis of bending is oriented parallel to the longitudinal direction of the bridge. Upon a successful validation and the verification of the computational model, several loading scenarios simulating different amounts of temperature increase in the presence of different soils adjacent to the abutment were simulated. Further analyses indicated that effects of the compaction level of the soil adjacent to the abutments, and of a magnitude of the thermal load on the substructure are opposite from the effects of these agents on the superstructure.

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1. Introduction

According to Burke [1] integral bridges were implemented in practice shortly after Cross [2] had developed a simple method for the analysis of continuous beams and frames. This enabled the design and construction of bridges without deck joints, which are known as integral bridges (IB). In 1935 Kansas was among the first states in the U.S. that constructed an IB (Bakeer et al. [3]). Since then the construction of integral bridges has been pursued by many states in U.S. and provinces in Canada.

At first IBs were built to eliminate the leakage of deicing chemicals and the resulting corrosion of primary structural members, which remains the main cause of limited service lives of jointed bridges. The additional benefits of IB, many of which turned out to increase their sustainability, are inherent to its geo-structural system. Economic benefits are accomplished through lowered whole life cycle costs including decreased construction and maintenance costs. Other benefits include elimination of noise associated with crossing of vehicular traffic over jointed bridges, and more pleasing aesthetics of a continuous superstructure. The social benefits comprise better connectedness for urban and rural environments, which is achieved through less maintenance caused traffic disruptions, and easier widening and future replacement of IBs. Furthermore, a vehicular ride quality is improved, and traffic safety is increased by elimination of joints. In addition, an IB is a continuous geo-structural system that results in more uniform distribution of internal forces than jointed bridges (Dicleli [4]). Consequently, IBs exhibit an increased redundancy and resilience.

The important uncertainty related to the design and performance of IBs is stress in piles. Cyclic loading such as temperature variations and traffic loads, can cause significant horizontal displacements of a bridge. A long term cyclic loading generates rotations and horizontal displacements of abutments that cause a settlement of the abutment backfill. During this process a void gradually forms behind an abutment, thus causing the soil pressure to further increase upon the subsequent expansion of the bridge. Consequently, IBs have to deal with greater soil pressures acting on the abutments than jointed bridges. Settlement of the abutment fill and movement of the superstructure can lead to cracking of the wing-walls and opening of joints between a bridge and an approach slab. Furthermore, due to settlement, and thermal changes and gradients creep and shrinkage of concrete and additional secondary stresses can develop in the superstructure.

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Additional disadvantages include minor longitudinal and transverse cracking, poor drainage at abutments, and cracking and spalling in bearing areas (Bakeer et al. [3]).

In spite of many advantages of IBs that outweigh their disadvantages there is still a need for knowledge discovery, which will help to further reduce the disadvantages of IBs.

2. Literature review

Although many studies, including those addressing field instrumentation, laboratory experiments, and numerical modeling have been carried out the lack of understanding of the behavior of IBs is still a concern. A brief overview of the research addressing primarily a numerical modeling of IBs is presented next in the chronological order.

Dicleli [4] had proposed a simplified structural model of an IB, on the basis of which a computer program was developed. The deck, abutment and piles were represented by structural elements having effective widths corresponding to the spacing between girders, which essentially extended into the abutment and piles, thus lumping the piles based on the tributary width. The program was capable of analyzing different loading scenarios separately and combining the corresponding results as needed, thus indicating that it was assumed that an IB remained in the elastic range. The proposed method produced more economic designs than the conventional analysis used previously.

Dicleli and Albhaisi [5] focused on the abutment-backfill system while evaluating the performance of IBs built on clay. They used the SAP 2000 software to conduct static push-over analyses on a 2D model, thus simulating a thermal load. They concluded that maximum length limit of IBs is controlled by the flexural capacity of abutment under positive temperature changes for the abutments taller than 4 m. They suggested that piles should be oriented about their weak axis of bending to enhance the maximum length limits as determined by the flexural capacity of abutment. Furthermore, they also suggested that pinned connection between the abutment and the pile head may be used to reduce the flexural demand on the abutment.

Dicleli and Albhaisi [6] conducted static pushover analyses of a pile–soil system by using a finite element-based software SAP 2000. Their model accounted for nonlinear responses of structure and soil. Dicleli and Albhaisi [6] found that the maximum length limits for IB with stub abutments decrease as the foundation soil becomes stiffer. They also found that the pinned abutment-pile connection significantly increases the displacement capacity of integral bridges with stub abutments based on the capacity of piles under cyclic loading. They concluded that maximum length limits of concrete and steel IB in moderate climates range from 180 to 320 m and from 125 m to 220 m respectively.

Huang et al. [7] used a P beam numerical model to model the prestressed concrete IB with a total length of 66 m located in Rochester, Minnesota. They compared numerical predictions with the actual measurements that were reported by Lawver et al. [8]. Based on the prediction of their numerical model they concluded that the creep rate of the concrete girder could have increased due to the increased backfill soil pressure. They also detected steadily increasing pile curvatures over seven years. They concluded that creep and shrinkage significantly affect behavior of concrete IB.

Civjan et al. [9] presented results of a 2D finite element analysis of an 82.3 m long three-span integral bridge located in Orange–Wendell, Massachusetts. The bridge has a concrete deck and steel girders. Two node elements with three degrees of freedom per node were used to model the bridge by using a GT STRUDL software. They modeled expansion and contraction of the bridge based on the comparison with the actual measurements. Civjan et al. [9] concluded that their computational model captured neither the transition from passive to active soil states, nor the peak active pressures. They also found that bending moments in piles were minimized by using a denser backfill.

Huang et al. [10] performed a 3D finite element analysis of a 66 m long three-span prestressed concrete integral bridge located in Rochester, Minnesota. They used shell and beam–column elements and ANSYS software. They modeled expansion and contraction of the bridge combined with gravity loads, but assumed no-contact between the abutment and soil in the case of the bridge contraction by using Winkler's springs with zero stiffness. Huang et al. [10] verified their computational model against the actual measurements and conducted a number of parametric studies assessing effects of several design variables. They concluded that the selection of the pile type and orientation should be based on balancing the stresses in piles and in superstructure for long span bridges or bridges surrounded by stiff soils. They recommended that the pile selection and orientation should be based on the specific bridge situation.

Pugasap et al. [11] used an ANSYS software to predict a long term response of IBs. Verification and validation was performed by comparing the numerical results with the field measurements obtained on three IBs in Pennsylvania over several years. Numerically obtained and measured soil pressures were found to be in a good agreement. In addition, it was shown that predicted abutment displacements and corresponding design moments and forces at the end of the numerically simulated 100-year period have a significant influence on a long term behavior which should be considered in IB design.

Kim and Laman [12] conducted a parametric study of a prestressed concrete IB by using a 2D numerical model. The imposed loads included a superstructure temperature loads including temperature gradients, and concrete time-dependent loads. Reponses of three different bridges with total lengths ranging from 18.3 m to 121.9 m were simulated in their study. They found that the magnitude of a thermal expansion coefficient significantly influences the axial force and bending moment in a girder, and lateral force and bending moment in the pile, as well as the pile/head displacement. They also found that the bridge length significantly influences axial forces in girders, lateral forces and the bending moments in piles, as well as the pile head displacement.

Kalayci et al. [13] studied the effect of an in-plan curvature on the thermally induced response of an actual IB located in Vermont, USA. They selected a two-span curved IB and subjected it to the temperature increase and decrease, each of which was equal to 55.6 °C. The bridge is 67.7 m long, 11.3 m wide, and it has 11.25° curvature. It has steel girders and concrete deck. Kalayci et al. [13] assembled a finite element model of the IB whereby the soil was modeled by non-linear Winkler's springs. They found that longitudinal displacements, earth pressures and weak axis bending moments in piles decreased with increasing curvature. Conversely, lateral displacements increased with increasing curvature.

To investigate the long-term effect of temperature variations on the superstructure of an IB, William et al. [14] monitored a newly constructed three-span IB in West Virginia for four years. The total length of the bridge is 44.8 m. It has steel girders and concrete slab. William et al. [14] developed a detailed three dimensional finite element (FE) model of the bridge by using an ADINA software. Comparison of the measured data and numerically obtained results showed a very good agreement of longitudinal strains in the middle girder, and longitudinal and transverse deck strains. They found similarly to Kalayci et al. [13] that the lateral displacements at the ends of steel girders increase with increasing skew angle. Additionally, their results show that the backfill and supporting piles restrain movement of the integral abutment, thus inducing axial

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