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Parametric study of an integral abutment bridge supported by prestressed precast concrete piles

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ABSTRACT

Integral abutment bridges (IABs) have been designed and constructed since the 1930s around the world. In these bridges, the water leaking problems and maintenance issues of expansion joints are minimized. However, the behaviors of IABs under temperature effects have not been completely understood. In the state of Louisiana, the first full IAB, i.e., the Caminada Bay Bridge, was built on the soft soil conditions in 2011. This paper presents a numerical investigation on the thermal performance of this bridge using ANSYS software. Based on the analysis studies, the numerical modeling methodology for IABs, i.e., temperature loadings, backfill–abutment interactions, and soil–pile interactions, is validated by comparing the bridge response with the field measurements. In addition, a parametric study is performed and demonstrated that the behavior of IABs is affected by temperature loadings, boundary support types, backfills behind abutments, soils surrounding piles, and pile–bent connections. It needs to balance all these parameters in designs so that the thermal deformation of slabs is appropriately accommodated without compromising the integrity of the superstructure and substructure.

1. Introduction

Integral abutment bridges (IAB) have been designed since the 1930s around the world. The main purpose was to replace traditional jointed bridges because expansion joints can affect the durability of bridges. Though with various terminologies, e.g., integral bridge, integral abutment bridge, jointless bridge, rigid frame bridge, and U-frame bridge, the IABs commonly share a similar structure configuration. A full IAB refers to a bridge where the superstructure (i.e., girder, deck slab, and approach slab) is casted monolithically with the abutment; and the abutment in turn is supported on a row of piles. Under such integral constructions, the water leaking and maintenance issues of expansion joints may be minimized. There are also some other advantages of jointless bridges, such as fast bridge construction, uniform lateral load distribution, and good resistance to catastrophic events [19,24].

The IABs, however, have not been widely applied in practice until now. It is partly due to the uncertainties of their behaviors under daily and seasonal temperature variations. No national design specifications exist, and the current designs and constructions primarily rely on empirical practices. Under these circumstances, some numerical studies have been conducted by researchers to analyze the responses of IABs under different structural and geotechnical conditions [11,4,23,8,12,14,9,22]. Specifically, Huang et al. [13] studied the effects of structural configurations, such as the hinged and fixed connection details at the abutment–pile cap, and the weak and strong axial bending of the steel and concrete piles; Civjan et al. [7] discussed the soil effects, such as the compact degrees of the backfills behind the abutments and the soil restraints around the upper part of the piles. However, the behaviors of IABs under different temperature effects, including the long term uniform temperature variations and short term daily temperature gradient, has not been fully understood; the superstructure and substructure of IABs under such temperature loadings deserve more in-depth investigations.

The first full integral abutment bridge, the Caminada Bay Bridge, was designed and constructed on the unique soft soil conditions in the state of Louisiana. This study was intended to investigate the responses of this bridge under different temperature effects. Specifically, a numerical 3D finite element modeling method was firstly proposed using the commercial software ANSYS 11.0 which was validated by the field monitoring measurements. Then, a parametric study was performed to study the thermal responses of IABs under different support conditions, backfill materials, soil types, and structural configurations.

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2. Finite element model validation

The numerical model for Caminada Bay Bridge is developed in this section. The modeling assumptions and parameters are firstly elaborated in details, including the bridge description, boundary condition, soil–structural interaction, loading cases, and model development. Then, this model is discussed and verified by comparing the simulation results with the field measurements.

2.1. Bridge description

The Caminada Bay integral abutment bridge is located at Grand Isle, LA, about 160 km to the south of New Orleans, LA. The detailed bridge configurations can be referred to Voyiadjis et al. [25], while the information adopted in this study is summarized here for the convenience of readers. The first eleven spans of the bridge are considered in the present numerical model. The superstructure includes a 3 m sleeper slab, a 12 m approach slab, and a ten span continuous concrete slab with each span of 9.1 m and a total of 91 m. The thickness of the slab is 0.46 m, and the width of the superstructure is 14 m with two 6.1 m lanes and one 1.8 m sidewalk. Each slab span is supported by a 1.2 m height abutment which in turn is supported by a single row of four precast prestressed concrete (PPC) piles with each 1 m diameter and 20–21 m long.

The material properties from the design calculation sheet and considered for the modeling of this bridge are as follows: (a) Class AA (M) concrete, with a strength of 28 MPa, is used for the slabs and bents; (b) Class P(M) high performance concrete, with a minimum compressive strength of 41 MPa at 28 days, and an average compressive strength of 69 MPa at 56 days, is used for the PPC piles; (c) Type 316LN stainless steel, with an elastic modulus of 200 GPa, a tensile strength of 515 MPa, and a yield strength of 205 MPa, is used for the reinforcing steels in the bents and slabs; (d) Grade 60 black steel, with a yield strength of 414 MPa, is used for all the other reinforcing steels; (e) Grade 270 steel, with a breaking strength of 1860 MPa, is used for the prestressing strands; and (f) the thermal expansion coefficient of the concrete is considered as 9 (10^{-6}/°C). It is noted that 10.8 (10^{-6}/°C) is specified in AASHTO LRFD [1], and the lower and upper bounds of 8.5 (10^{-6}/°C) and 11.7 (10^{-6}/°C), respectively, are specified in the ACI [2].

2.2. Boundary condition

The integral joints of IAB are generally constructed at the interfacial locations of the slab–girder–abutment at two exterior ends. However, the bridge discussed in this study has more complicated connection behaviors throughout the first eleven spans. First, at the left end of the bridge, a 10.2 cm expansion joint is provided between the sleeper slab and approach slab; and the approach slab, in turn, is laid on a reinforced rubber pad. Thus, the restraint to the horizontal movement of the approach slab from the rubber is expected minimum during the first several years of monitoring periods. Second, for all the interior bents from Bent 1 to Bent 10, the tensile steel rebars are constructed both extending from the bents to the slabs and also from the pile heads to the bents. Thus, moment continuous scenarios are expected at these locations. Third, at the right end of Bent 11, a strip seal joint is applied between the slab and Bent 11 so that the longitudinal movements and rotations are not fully restrained. Therefore, the boundary conditions for the present bridge are modeled as simply supported conditions at the two ends and fixed ones in between.

2.3. Soil structural interaction

The soil boring log information near Bent 1 is adopted to represent the soil condition at the bridge modeling site. The soil layers with similar properties, as shown in Fig. 1(a), are combined and used in the numerical model as shown in Fig. 1(b). It can be observed that the soils are generally categorized into three layers, including a layer of medium clay for the backfill followed by two layers of medium sand and medium clay below the water table and surrounding the piles, respectively. The soil properties in Fig. 1 are defined as: γ = the total unit weight of soil (kN/m^3), γ' = the effective unit weight of soil (kN/m^3), ε_{50} = the axial strain at one-half of the peak stress difference from a tri-axial test, K = the soil modulus (kN/m^2/m), C = the undrained shear strength of clay (kN/m^2), and Φ = the internal friction angle of sand (degree).

In this study, the soil–pile interaction behavior is accounted by a series of p–y curves along the pile depths, where the p and y refer to the soil force and pile deflection, respectively. The p–y curve method is based on the Winkler hypothesis. The soil is simplified as a series of discrete elements such that the soil response at one point is independent of the pile deflection elsewhere. The generations of p–y curves are affected by some parameters, e.g., soil type, shear strength, moisture condition, effective stress, stress history, loading condition, etc. Based on the different soil parameters shown in Fig. 1(a) and (b), the p–y curves are generated through the COM624P program [26] for representative depth below surface, as shown in Fig. 1(c).

In modeling of the backfill–abutment interaction, the NCHRP [20] curve, as shown in Fig. 2, is considered in the present study. The force and displacement (F–D) relationships between the backfill and abutment are expressed as,

$$F = K\sigma'_v wh \tag{1}$$

where F = effective soil lateral resistance; K = coefficient of lateral earth pressure for the passive K_p and active K_a conditions, respectively, determined by the ratio of the wall deformation and height (D/H); σ'_v = vertical effective soil stress, equal to the soil density multiplied by the depth of the soil ($\gamma' z$); and w and h = width and height dimensions of the tributary area of the abutment backwall, respectively. For the cohesive backfills as the medium clay behind the abutment of this bridge, however, there are no appropriate design curves available in the codes or reports based on the authors' knowledge. According to the Caltrans [5] and Canadian Geotechnical Society manual [6], for cohesive soils, the creep effects should be considered in estimating the design earth pressures. Since obtaining these soil behaviors is complicated and requires laboratory tests, the cohesive or other fine-grained soils are often avoided as backfill materials. Thus, the backfill effects are not considered in the present analysis. This assumption can be justified from the field measurements reported by Voyiadjis et al. [25] and Kong et al. [17], in which the observed variations of the pressures for such soil types under the current IAB configurations are negligibly small.

2.4. Loading cases

Uniform and gradient variations are two major temperature components considered in a bridge thermal analysis. The temperatures within the bridge may fluctuate at various components and locations, while the major temperature variations of the present bridge primarily appear in the superstructure based on the field measurements as reported by Voyiadjis et al. [25] and Kong et al. [17]. In that field monitoring program, the temperatures of the superstructure are measured at the top and bottom surfaces. Thus, the temperature distribution patterns through the depth of the superstructure are numerically predicted. Using the temperature predication methods [10,18], the bridge temperatures during two representative hottest and coldest weeks, i.e., from 01/03/2012 to 01/13/2012 and from 09/06/2011 to 09/16/2011, respectively, are simulated. The boundary conditions, i.e., ambient